VOLUME VIII APRIL, 1943 NUMBER 2

GEOPHYSICS

A Journal of General and Applied Geophysics

MULTIPLE BRANCHES IN SEISMIC REFLECTION-TIME SURFACES*

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ABSTRACT

When for a given shot-point and receptor more than one reflection is recorded from a given reflecting bed, the corresponding reflection-time surface may be said to be multiply branched. Although multiple branches are difficult to evaluate, serious errors in mapping may result when their presence is overlooked. A method is therefore proposed for the interpretation of field data to account for this phenomenon. The conditions for branching and its properties are considered, showing that branches must occur in odd-numbered sets and in certain type forms, which are illustrated.

OCCURRENCE OF MULTIPLE BRANCHES

Frequently encountered in dip shooting is evidence that a particular reflecting bed is distorted to such a degree as to yield more than one reflecting point for a given shot-point and receptor. Such evidence may appear in the form of reflection interference and conflicting move-outs on individual records; or the reflecting bed as mapped may indicate that the condition of multiple reflecting points may exist; or else a confused scattering of computed strikes and dips may evoke a verdict of multiple reflecting points to explain the lack of coherence in the data. The type of stratigraphy which is involved may vary from a relatively shallow and extremely distorted section to a very deep section of moderate relief.

Although the complexity introduced by the condition of multiple reflecting points renders difficult a clear-cut evaluation of the subsurface structure, certain fundamental properties associated with the geometry of the problem can be derived which may aid in clarifying

* Manuscript received December 1942.

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the picture.[1] The rules which will be established are therefore proposed as a method of analysis of the condition of multiple reflecting points.

Since the major question involved in dealing with a situation in which multiple reflecting points occur lies in the method of integrating the observed reflection-time data, the method of attack will best be served by utilizing the concept of reflection-time surfaces.[2] From every point on the reflecting bed which is under investigation, consider that a normal ray, *i.e.*, a ray which strikes the bed at right angles, is drawn to the ground surface. Reckoning reflection-time for any position on a ray as the travel-time along the ray from that position down to the bed and return, one may conceive of surfaces of constant reflection-time, or so-called "iso-time surfaces," at right angles to the normal rays. The reflection-times at the ground surface when plotted against the coordinates of the points of observation constitute the "reflection-time surface," which may be represented by time contours.

Bearing in mind that only an individual reflecting bed is being treated, one notes that, as long as none of the normal rays crosses another, at any position in the medium a *single* reflection-time is associated by normal rays with its incidence point on the bed. When, however, any crossing of the rays occurs, there will be positions in the medium with which more than one incidence point is to be associated and consequently more than one reflection-time. The iso-time surfaces passing through the latter positions in the medium are then said to be multiply branched, and correspondingly the reflection-time surface observed at the ground level becomes multi-branched.

For every flexure on its surface, a reflecting bed becomes a potential cause of crossing rays. However, the crossing will not occur below the ground level, as it must do to produce multiple branches, unless curvature of the reflecting bed becomes sufficiently severe. Where the subsurface zone is essentially constant in velocity, the rays may be approximated by straight lines, and the crossing of adjacent rays occurs at the center of curvature of that portion of the reflecting bed from which the rays radiate. Where velocity increases with depth and is essentially constant in the lateral direction, the rays become curved,

[1] For an equivalent effect of multiple-valued curves in refraction shooting, see Louis Slichter, *Theory of Interpretation of Seismic Travel-Time Curves in Horizontal Structures*, Physics, Vol. III, No. 6 (Dec. 1932), p. 273.

[2] M. B. Widess and N. A. Haskell, *The Computation and Mapping of Seismic Reflection Data*, GEOPHYSICS, Vol. V, No. 2 (April 1940).

with a consequent rise in the point of crossing of adjacent rays. Accordingly, a curved reflecting bed which may produce multiple branches if the velocity above the bed is essentially uniform may not produce multiple branches if the velocity above the bed decreases towards the ground surface.

BASIC ASPECTS OF A TWO-DIMENSIONALLY CURVED BED

A simple class of structures leading to multiple branches in the reflection-time surface is a two-dimensionally curved trough, an

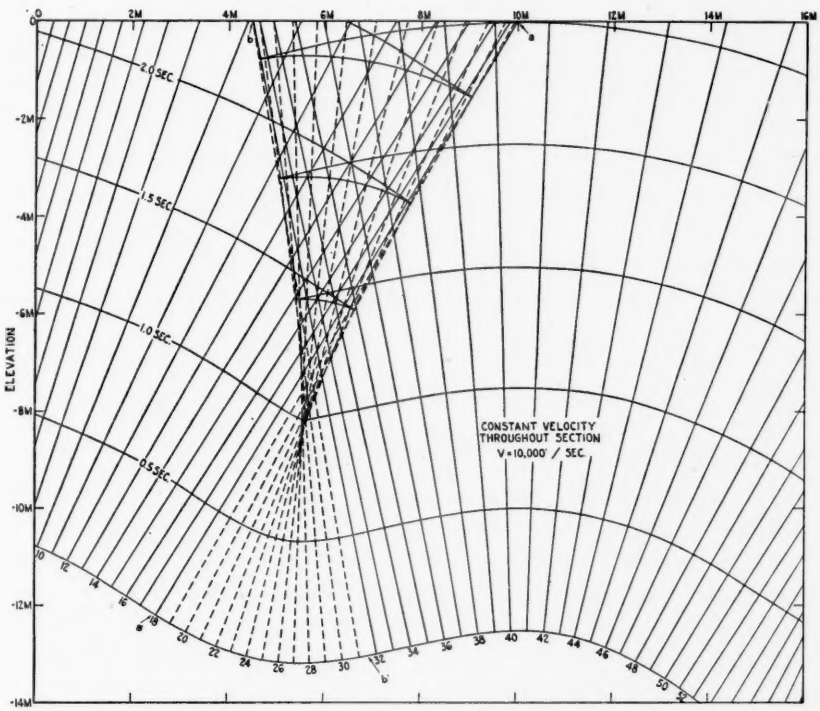

FIG. 1. An example of two-dimensional curvature, showing normal rays and multi-branched iso-time surfaces.

example of which is shown in Fig. 1. The particular bed pictured is an inclined sinusoidal undulation blending into a homocline. For further simplification, the velocity in the section is considered to be constant. Iso-time surfaces for the reflecting bed are drawn, single branched near the bed and multiply branched beyond a time of about 0.9 seconds where rays begin to cross. The reflection-time at the ground

level is given by the time section, Fig. 2, where, in the usual manner, the observed reflection-time is plotted against position of the observation.[3]

The reflection-time section in Fig. 2 consists of a continuous line which undergoes two reversals in direction; at each reversal a new branch is formed, a total of three branches being represented. Every branch is essential to an accurate evaluation of the contours of the complete reflecting bed. The omission of branches or the confusion between branches may result in a serious error in the deduced structure, and it is for that reason that an attempt must be made to examine the individual branches and to recognize their properties.

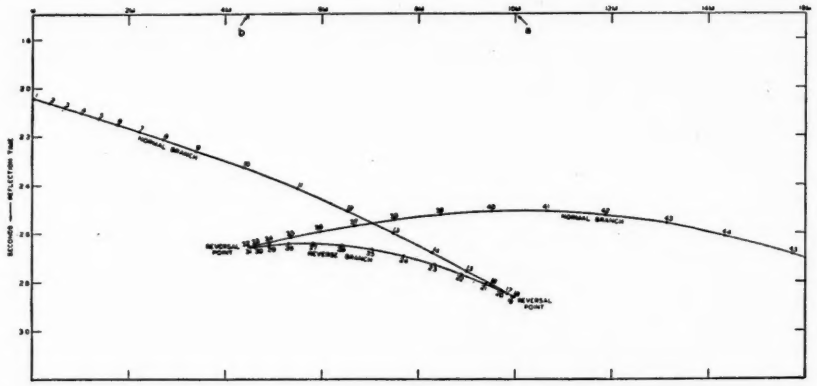

FIG. 2. Multi-branched reflection-time section for structure shown in Fig. 1.

One such property for two-dimensional curvature of the reflecting bed is derived from the fact that if the reflecting bed and its slope are continuous, a continuous line of observation points on the ground surface will yield a continuous line of incidence points on the reflecting bed. Accordingly, if a branch is observed at all, it will be observed in a continuity of points until it joins the other branches.

Another important property of branches is their occurrence necessarily in odd multiplicity, again under the stipulation of a reflecting bed which is continuous and possesses continuous slope. This property

[3] Although an infinitesimal spread length is considered, for the purpose of the present discussion a ray striking at any point on the ground surface may be treated as approximately equivalent to a ray from a shot-point on one side of that point down to the reflecting bed and back to a receptor at an equal distance on the opposite side of the point, a time correction for the diagonal character of the ray path being applied.

becomes evident by considering, for example, the section of Fig. 1. Beginning at the extreme left of the section, as one progresses along the reflecting bed toward the right, the normal rays emanating from the bed intersect the ground surface at points moving also to the right. Then, after one passes point a' on the reflecting bed, the normal ray intersections at the ground surface begin to move to the left, since the rays cross. This direction of motion at the ground surface, however, cannot last indefinitely because the rays cannot continue to cross, and, when point b' is reached at the reflecting bed, the direction of motion of rays at the ground surface resumes its normal direction to the right. During the entire course of movement along the reflecting bed, therefore, normal rays had covered the area a to b at the ground surface three times. With a more complex reflecting bed it is conceivable that the reversal of direction of movement of normal rays at the ground surface could be more numerous than in the above example, but in all cases the reversals must be even numbered and therefore the branches odd numbered.

The significance of a situation in which odd multiplicity in branches is encountered lies in the increased difficulty of analysis which a condition of multiple branches presents, introducing greater complexity than might at first be supposed. If, for example, it is believed that an observation point is recording two reflections from a given stratum, that stratum must also be producing a third reflection at the observation point, and the records should be examined for indications of its presence. Hence, a bed which is so distorted as to cause crossing of normal rays is a potential producer of at least three sets of reflections in some areas of observation. However, if the bed and its overlying stratum are not uniform, the bed may not possess a constant coefficient of reflection along its extent and some of the reflection branches may possibly be too weak to be recorded.

Another cause for difference in relative amplitude of the component branches is the degree of focusing or divergence of the seismic wave by the reflecting areas. Normal rays drawn from equally spaced points along the reflecting bed, as in Fig. 1, exhibit to a useful approximation this energy concentration or rarefaction. The figure illustrates that the multiple branches may each possess energy at least comparable to that returned from a plane reflecting bed and accordingly that all three branches may be prominently represented on records.

If fracturing in the trough of a structure occurs, reflections from

this area may be largely obliterated, with incoherent energy appearing on the records, and with the result that a branch may be lost. An analogous situation arises in the event of faulting whereby the so-called diffraction waves emanate from centers of secondary radiation at the fault plane.[4] The condition for continuity of reflecting bed and of its slope is not satisfied by a faulted bed, and therefore odd multiplicity of branches will not necessarily be realized. Nevertheless the method of analysis for multiple branches might be applied to the drag surfaces.

ANALYSIS OF A MULTIPLY BRANCHED REFLECTION-TIME SURFACE

Where a reflecting bed exhibits curvature without torsion, the observed data can be handled by use of time sections alone. Where appreciable torsion or twisting of the bed occurs, however, the data for the reflecting bed cannot be adequately treated without preparation of a reflection-time contour map.

In Fig. 3 is given an example of an idealized reflecting bed which changes gradually from a homocline to a tilted sinusoidal undulation, for which the north-south Section A–A is shown in Fig. 1. At the extreme western edge of the map, where dip is homoclinal, multiplicity of branches cannot exist, while at the east portion of the map, where the north-south section is sinusoidal, the time section, Fig. 2, indicates the presence of multiple reflection-time branches. The reflection-time surface is therefore singly branched at the west edge and develops branches as it progresses eastward. In Fig. 4 the reflection-time map for the structure is shown, having been computed on the basis that the transmitting medium has a constant velocity of 10,000 ft./sec.

In treating reflection-time branches it will be convenient to differentiate between *normal* and *reverse* branches. The *normal* branch will be defined as one such that in the vicinity of any point on that branch, the normal rays for the branch do not cross, while, if any rays cross, the branch is said to be *reverse*. Along a line of observation which is directed across the axis of structural folding, as for example Section A–A, the normal branches intersect and their edges are joined by the reverse branch, as shown in Fig. 2. Along a line of observation such as Section B–B which parallels the axis of folding, and which indicates

[4] Frank Rieber, *Visual Presentation of Elastic Wave Patterns Under Various Structural Conditions*. GEOPHYSICS, Vol. I, No. 2 (July, 1936).

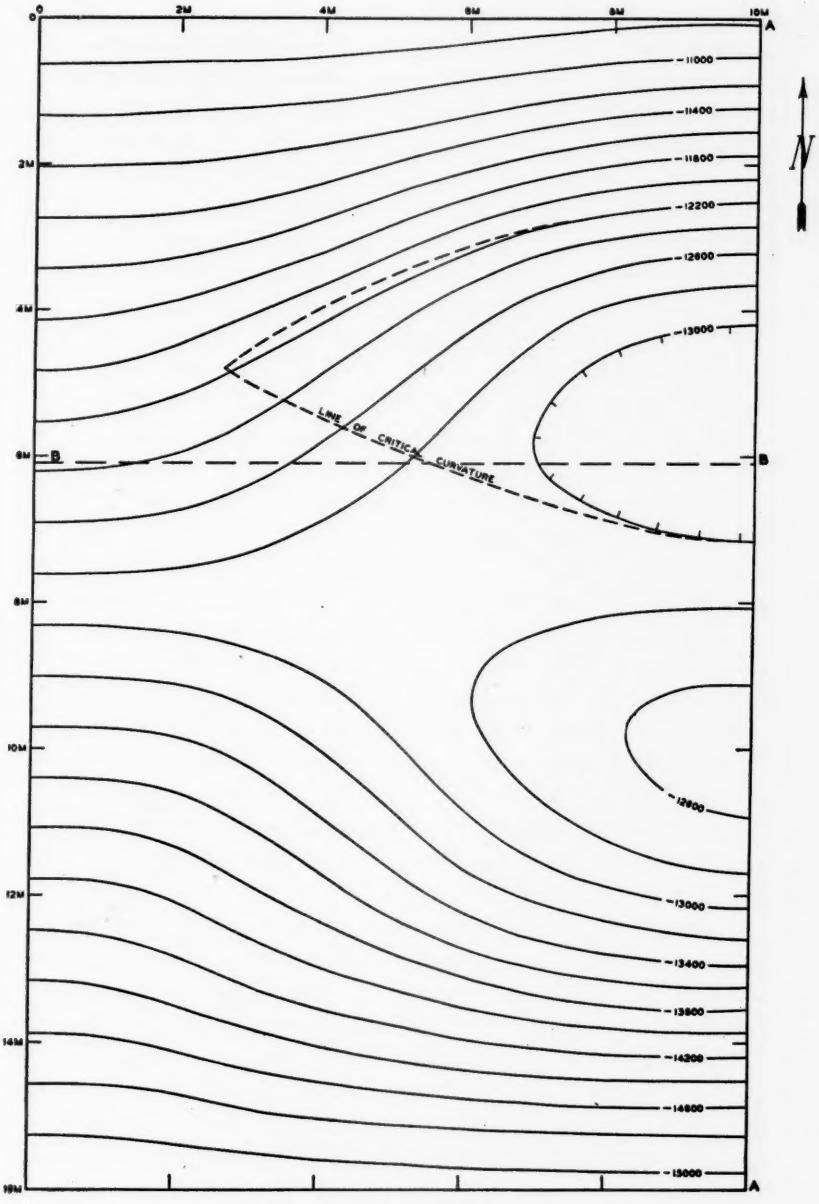

FIG. 3. An example of reflecting bed exhibiting prominent torsion. The section through A–A is shown in Fig. 1.

the extent of torsion in the reflecting bed, one normal branch proceeds uninterruptedly across the section while the second normal branch and the reverse branch appear on the section when the line of observation reaches a point, the so-called *reversal* point, from which incidence is at critical curvature of the reflecting bed, as shown in Fig. 5. If this section were to be continued eastward, depending upon the type of reflecting bed which would follow, the second normal branch and the reverse branch would again meet and then both disappear, or else the second normal branch would survive while the reverse branch would meet the first normal branch and then these two would disappear.

The reflection-time surface mapped in Fig. 4 depicts the crossing of the two normal branches, Section A–A, and the development of a second normal branch and a reverse branch, Section B–B. A section which exhibits crossing of normal branches, such as Section A–A, will be termed a "cross-branched" section while that which does not involve crossing of normal branches, such as Section B–B, will be referred to as a "laterally-branched" section.

The reflection-time map constitutes the completed integration of data which are secured from observation points on the ground surface. If the individual observations are accurate and the velocity of the section is known, the reflection-time map can be transformed to a unique and accurately located bed by utilizing the established reflection-ray relations between reflection-time and move-out which are recorded and dip and depth at the incidence point.[5] Such relations are applicable to each branch whether it is normal or reverse.

The present problem is to determine a method, when branching occurs, of carrying reflection-time traverses along observation lines in order to prepare a reflection-time map.

Because individual branches of a multiple set must of necessity meet other branches, reflections for branches must suffer interference in the vicinity of their junction. If curvature along all of the reflecting bed does not exceed greatly the critical magnitude required for branching, the multiple branches will at no time be greatly separated in time, so that distorting interference may permeate the entire region over which multiple branches are encountered. In addition, the reflections from neighboring strata may be a source of interference. Nevertheless, even though reflections cannot be picked accurately under these circumstances, the recognition that a condition of multiple branching

[5] Widess and Haskell, *loc. cit.*, p. 159.

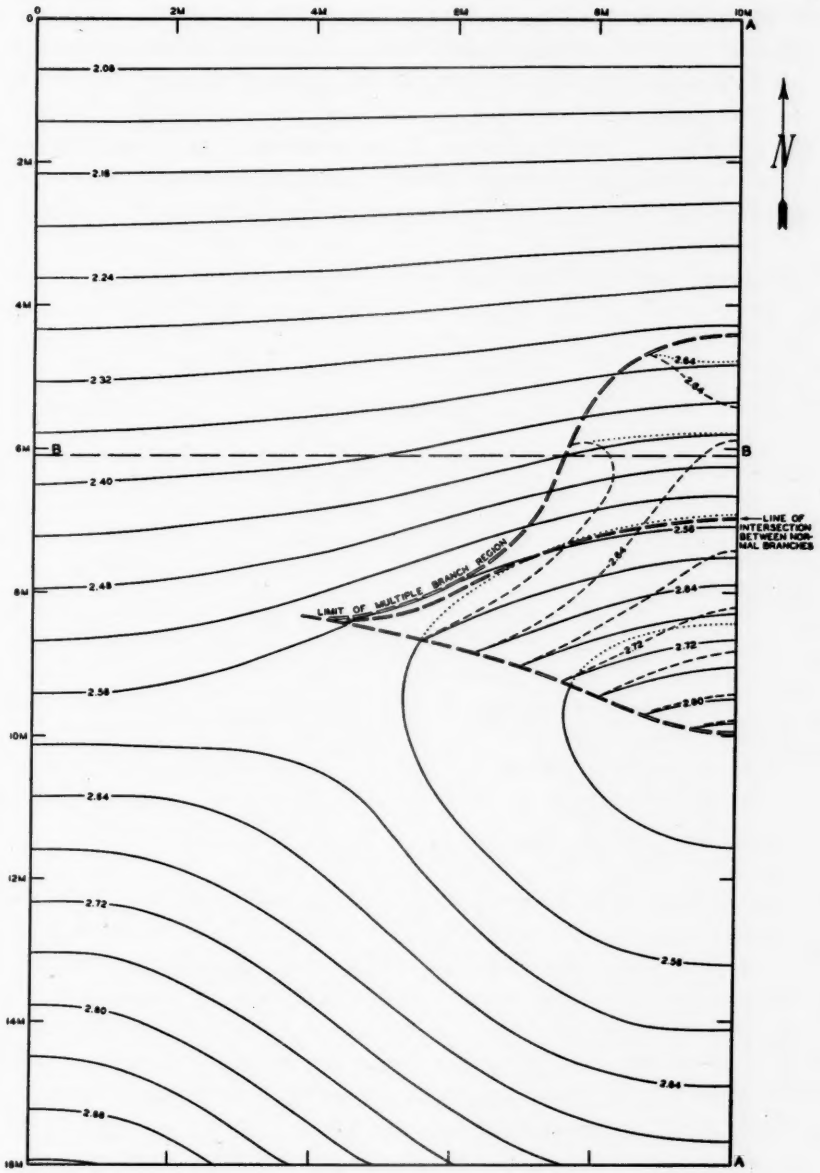

FIG. 4. Reflection-time map for the structure shown in Fig. 3. Solid and dotted lines indicate the normal branches, while the light dashed lines indicate the reverse branch.

exists is not necessarily valueless. The lowest point of a structure which is producing multiple reflections is in general to be found from the reverse branch. If, therefore, the region of multiple branches is omitted, and with it the reverse branch, a map will result which will not show the full extent of relief. It is possible that this diminution of relief may make the difference between mapping a reversal in dip and mapping no reversal, as in the example of Fig. 2, wherein the omission

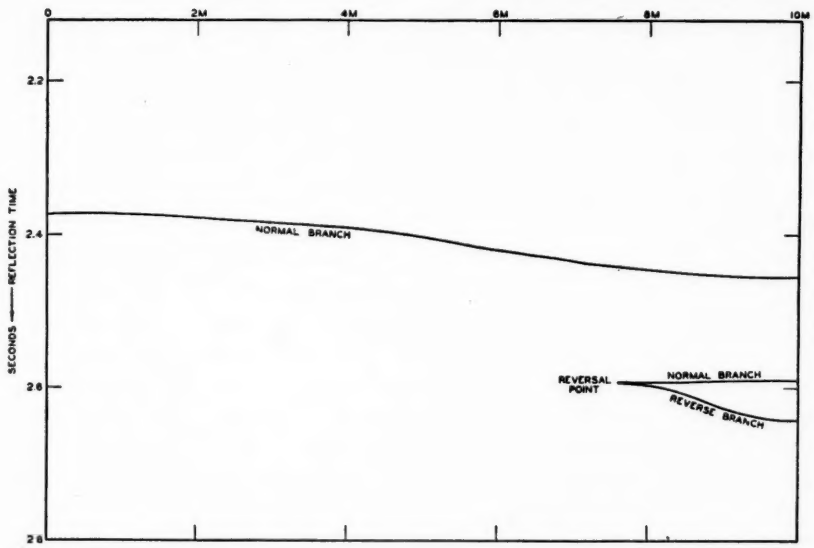

FIG. 5. Reflection-time along laterally-branched section, Section B–B in Fig. 4.

of the entire region of multiple branches would show only flattening whereas in actuality a strong reversal in dip exists.

In general, if the stratum in question persists as a prominently reflecting surface, some reflection-time data will be obtainable in the region of multiple branches. The points of reversal, at which branches join tangent to each other, represent a concentration of energy, since these points result from direct focusing by a reflecting bed with critical curvature. Also, branches terminate abruptly when reaching points of reversal. Evidence for reversal points might therefore be gained from continuous profiling by locating the gradual growth of energy of a reflection followed by its sudden disappearance, although assuredly such evidence does not exclude other causes.

Reflections may be legible over segments of the multi-branched

region if the structure is sufficiently sharply curved and broad that a sizable time interval is developed between the branches, provided that reflections from neighboring strata do not interfere excessively.

Sufficient data might thus be accumulated to permit piecing together the complete multi-branched time section. In the case of a cross-branched time section, the observed time gradients are to be paralleled, or, if correlations are available, a line is to be drawn through correlation times, until the points of reversal are reached. The necessary requirement in drawing the reverse branch in a cross-branched section is that it should terminate tangent to the ends of the normal branches and that it should be of a convex-upward shape, of sufficient curvature that all adjacent rays along the reverse branch cross before reaching the ground surface.

In the case of laterally-branched time sections, the problem of traverse running is considerably different from that of cross-branched sections. It might be well first to examine the original data to ascertain whether the section in question appears to be across the axis of folding and is potentially a cross-branched section or whether it parallels folding and therefore may be laterally branched. In the latter case, analysis is directed toward isolating those normal branches which will serve to close traverses carried on cross-branched sections. If a dip phantom paralleling observed gradients is being run, difficulties might arise in differentiating between the gradients of the various branches. Fortunately for this eventuality, the gradients of the branches do not differ greatly in the case of a laterally-branched section as, for example, is shown by Fig. 5. If scattered correlations can be recognized, care must be exercised to avoid interpreting correlation picks displaced by a large interval of time as evidence of faulting or strong dip since picks from different branches might have been made. In general, multiple branches must be analyzed largely by cross-branched sections and the information so gained applied to laterally-branched sections in an effort to isolate the branches.

The case of multiple branches in reflection-time surfaces and the proposed method of analysis will now be summarized. Where a reflecting stratum is continuous, its slope continuous, and its surface appreciably reflective throughout, continuity of reflections is to be expected for all points on the ground surface. If, therefore, at an observation point on the surface, a record is believed to exhibit more than one reflection from a given stratum, there should be some points in the neighborhood of that observation point which should also re-

veal more than one reflection from the stratum. When this is not realized, the conclusion of multiple branches is to be regarded as in error, due possibly to misinterpretation of time gradients on the record. When, however, support for two reflections from a given stratum is found at nearby observation points, and multiplicity is therefore concluded to exist, a third set of reflections *must* be expected to be present and indications for the third branch are to be sought on the records. Three sets of reflection-times, with strong opportunity for interference between reflections, would therefore be expected to exist if the original observation of a *single* instance of two reflections were correct.

Preparatory to differentiating reflections between the various branches, the section in question is to be classified on the basis of preliminary examination of data as being either cross-branched or laterally-branched. Records are then to be studied for evidence of reversal points, as indicated by prominent reflection energy which is suddenly terminated, and for legible reflection-time gradients or correlations. In cross-branched sections a time traverse is run as far as the reversal points by carrying data associated with the normal branches; the reverse branch is drawn tangent to the normal branches at the reversal points and with a convex-upward shape between the reversal points. The laterally-branched section is concerned primarily with the determination of those branches which persist on the section between tie-points, other branches appearing largely as a source of hindrance.

An evaluation of all existent reflection-time branches is essential to the knowledge of the complete reflecting structure. Omission of the entire region where multiple branches are encountered or confusion between time gradients of various branches will result in less relief of the computed bed than exists and may be responsible for the oversight of a closed structure. A careful attempt is therefore warranted, first, to detect that a condition of multiple branches exists and, second, to determine the traverse along *each* of the component branches.

The author wishes to express appreciation to the officers of Stanolind Oil and Gas Company and Western Geophysical Company for release of this paper for publication.

COMPUTATION OF SEISMIC DIPS BELOW AN UNCONFORMITY*

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ABSTRACT

Formulas giving the strike and dip of a plane reflector beneath a series of layers separated by interfaces of known strike and dip are developed in terms of seismic data obtained at the surface. The formulas for the position of a plane reflector beneath a single unconformity are also developed. Examples show the extent of the influence of the strike and dip of a single unconformity on the computation of the strike, dip, and position of the reflector yielding a given set of surface data.

INTRODUCTION

In order to proceed with the interpretation of reflection seismograph data it has been necessary to make some rather severe simplifying assumptions. For example, all of the earlier work was interpreted on the assumption that the ray paths were straight lines, which implies that the velocity of the section is constant. It was well-known that the velocity was actually not constant, so various adjustments were made to bring the interpretation closer to the facts. One natural assumption is that the velocity distribution can be approximated with sufficient accuracy by an ideal velocity distribution in which the velocity increases linearly with depth. This, of course, leads to circular arc rays and spherical wave fronts. It is found that the necessary computations can be carried out in this case almost as easily as in the former straight-line case. Another alternative procedure has been to use a standard time-depth curve derived from well shooting or from refraction data.

In each case progress is made by eliminating any gross errors that are introduced into the computations by over-simplification in our set of hypotheses. Gross errors of this type may present themselves as inconsistencies in the resulting interpretation. By gross errors we mean principally situations in which dipping reflectors are forced to cross through each other at appreciable angles. Of course, there will be observational errors due to our lack of ability to read the records with sufficient accuracy. The gross errors will usually stand out over and above these errors of observation. As an example, a gross error occurs when one passes over a rather narrow, deep syncline, using too low a

* Presented at the annual meeting, Denver, Colorado, April, 1942.

† United Geophysical Company.

‡ Consolidated Engineering Corporation.

velocity for the computation of the reflecting interfaces. In such a case the syncline can be made to appear as an anticline. Of course, we always wish to avoid errors of this sort. However, as in the present case, such an error may not appear as an inconsistency. It is therefore important to point out that consistency in itself is only a *necessary* condition, but is by no means a *sufficient* condition for the correctness of our resulting picture. Thus, we use inconsistency as a symptom of a pathological condition in our framework of hypotheses.

If the section we encounter consists of recent slightly dipping layers of relatively low velocity resting upon an older unconformity surface covering steeply dipping layers of high velocity, then our usual simplifying assumptions regarding the velocity of the section are no longer usable. It therefore becomes necessary to replace our older assumptions by a new set which we hope will correspond more closely to the facts. Our test of this correspondence will, of course, be related to the improved consistency of the interpretation.

We may note at the outset that if there is a relatively high velocity contrast between the upper section and the lower section, then the dip of the unconformity interface will have a very strong influence upon the apparent dip of the reflector as viewed from the datum surface by means of crossed lines of geophones.

In this paper we develop the formulas that give the strike, dip, and position of a plane reflector beneath a plane unconformity which separates two regions of constant velocity. A numerical example is given showing how the strike and dip symbol corresponding to a given set of reflection data is moved about on a map in accordance with the strike and dip of the unconformity. Another numerical example is included to show the effect on the strike when all dips are small. A general formula is also given for determining the strike and dip of a reflector beneath a larger number of layers of constant velocities and separated by plane contacts, or interfaces, of known strike and dip.

In applying these formulas the data for computation required consist of the strike and dip of the unconformities or plane contacts in question, the velocities of the regions in which the wave travels, and the usual reflection seismograph data obtained by recording waves at two perpendicularly intersecting equal spreads of seismometers symmetrically located with respect to the shot point. The formulas may be readily extended to other field setups.

TWO LAYER PROBLEM

Referring to Fig. 1, the source of the seismic wave pulse is assumed to be located at the point O in the datum plane. The ray to be reflected travels downwards from O through a medium of velocity V_1 to a point P in the refracting plane separating the medium of velocity

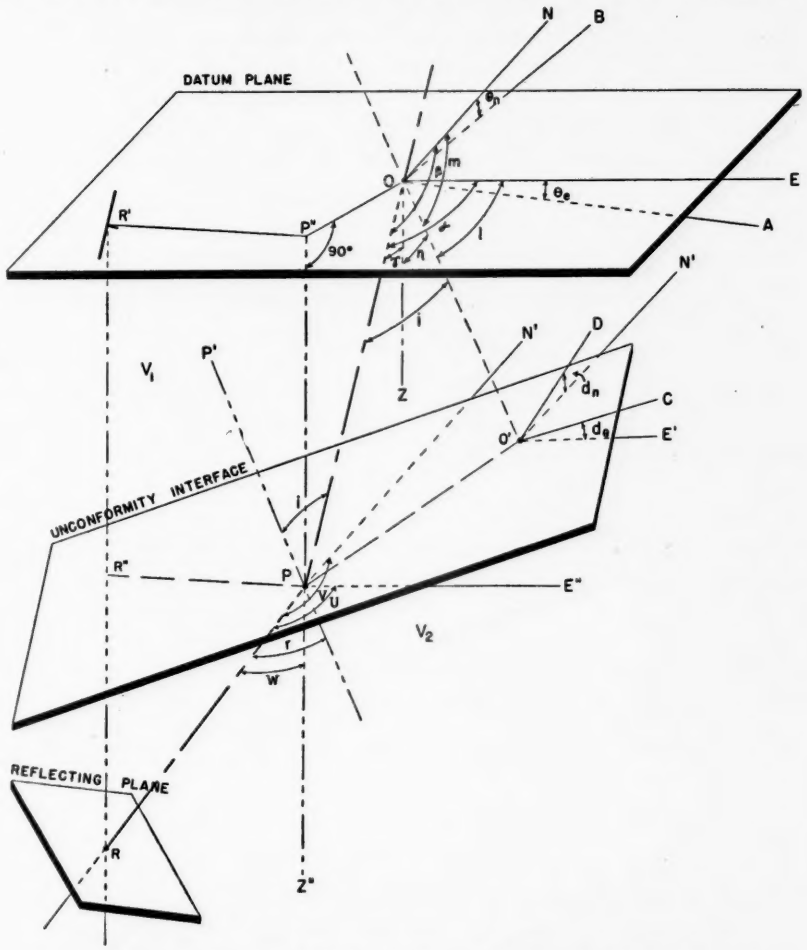

FIG. 1. Geometric diagram utilized in setting up the theory of the effect of an unconformity interface on the determination of the dip, strike and location of a reflecting plane in the two layer problem. The velocity between the datum plane and the unconformity is assumed to be a constant, V_1, and that between the datum plane and the reflecting plane a constant V_2.

V_1 from the medium of higher velocity V_2. The ray OP forms an angle i with the perpendicular PP' to the refracting plane. i is the angle of incidence upon the refracting plane and r is the angle of refraction, turned in accordance with Snell's law. The ray then goes from P to R where it is reflected back on itself, retracing all its steps.

From the reflection data we can easily get quantities which determine the direction of the ray OP. One such set of quantities is the set of direction cosines cos α, cos β, and cos γ of OP referred to the mutually perpendicular unit vectors $\boldsymbol{I}$, $\boldsymbol{J}$, and $\boldsymbol{K}$, pointing north, east, and vertically downwards, respectively.

The corresponding direction cosines of the refracted ray PR are cos U, cos V, and cos W.

For the particular reflection under consideration, where we shoot in the north-south direction we work in the plane determined by the direction of our profile, ON, and the ray OP. This is the plane in which our section is drawn—at least down to its intersection with the refracting plane. Thus by drawing the line OB in the plane PON and perpendicular to the ray OP, we get a line which is tangent to the upcoming wave-front at the point O. The angle between ON and OB is denoted by θ_n on the figure. Observe that

$$\beta = 90^\circ + \theta_n. \tag{1}$$

Hence β is determined as soon as θ_n is determined, and θ_n may be determined from the well-known formula:

$$\sin \theta_n = \Delta t_n (V_1/\Delta x) \tag{2}$$

where Δt_n is the north component of time step-out for the given reflection, and Δx is the corresponding distance step-out. Similarly,

$$\alpha = 90^\circ + \theta_e \tag{3}$$

and

$$\sin \theta_e = \Delta t_e (V_1/\Delta x). \tag{4}$$

The angle γ is the resolved dip angle using θ_n and θ_e for north and east components. This is derived from the identity

$$\cos^2 \alpha + \cos^2 \beta + \cos^2 \gamma = 1$$

from which we get

$$\cos^2 \gamma = \cos^2 \theta_e - \sin^2 \theta_n.$$

To summarize, the direction-cosines of OP are

$$\cos \alpha = -\sin \theta_e \tag{5}$$

$$\cos \beta = -\sin \theta_n \tag{6}$$

$$\cos \gamma = (\cos^2 \theta_e - \sin^2 \theta_n)^{1/2}. \tag{7}$$

In order to keep the signs straight, we must take θ_n and θ_e as positive for north and east dips respectively and negative for south and west dips respectively.

The dip of the refracting plane may be obtained by reflections off of this plane or by refraction shooting. The dip by reflection shooting is obtained just as outlined above.

By shooting north-south and east-west refraction lines we get two cross-sections that are each perpendicular to the refracting plane and therefore intersect in the line OO' which is the perpendicular dropped from the point O to the refracting plane. The direction of the line OO' completely determines the dip and strike of the refracting plane, and *vice versa*. Let the direction cosines of OO' be cos l, cos m, cos n. The angles l and m can be measured directly from the two cross-sections or we can refer to the component dip angles d_n and d_e in these cross-sections.

Then, the direction cosines of the perpendicular to the refracting plane are

$$\cos l = -\sin d_e \tag{8}$$

$$\cos m = -\sin d_n \tag{9}$$

$$\cos n = (\cos^2 d_e - \sin^2 d_n)^{1/2}. \tag{10}$$

At this point in the derivation, it is convenient to introduce four unit vectors which are defined as follows:

$\boldsymbol{R}_i$ = a unit vector parallel to the incident ray
$$= \boldsymbol{I} \cos \alpha + \boldsymbol{J} \cos \beta + \boldsymbol{K} \cos \gamma \tag{11}$$

$\boldsymbol{R}_r$ = a unit vector parallel to the refracted ray
$$= \boldsymbol{I} \cos U + \boldsymbol{J} \cos V + \boldsymbol{K} \cos W \tag{12}$$

$\boldsymbol{p}$ = a unit vector normal to the refracting surface
$$= \boldsymbol{I} \cos l + \boldsymbol{J} \cos m + \boldsymbol{K} \cos n \tag{13}$$

$\boldsymbol{q}$ = a unit vector in the line at the intersection of the refracting surface and the wave travel plane ($\boldsymbol{p}$, $\boldsymbol{q}$, $\boldsymbol{R}_r$ coplanar).

The relationship of these vectors to each other is shown in Fig. 2.

An inspection of Fig. 1 will show that the dip symbol will point towards the point P and not toward O (unless the plane determined by OO' and P happens to be vertical). Hence, we must locate the point P. To do this we must find the length of OP. This we can do by using

$$\overline{OP} = \overline{OO'}/\cos i \tag{14}$$

where $\overline{OO'}$ is the distance from the refracting plane to the point O and

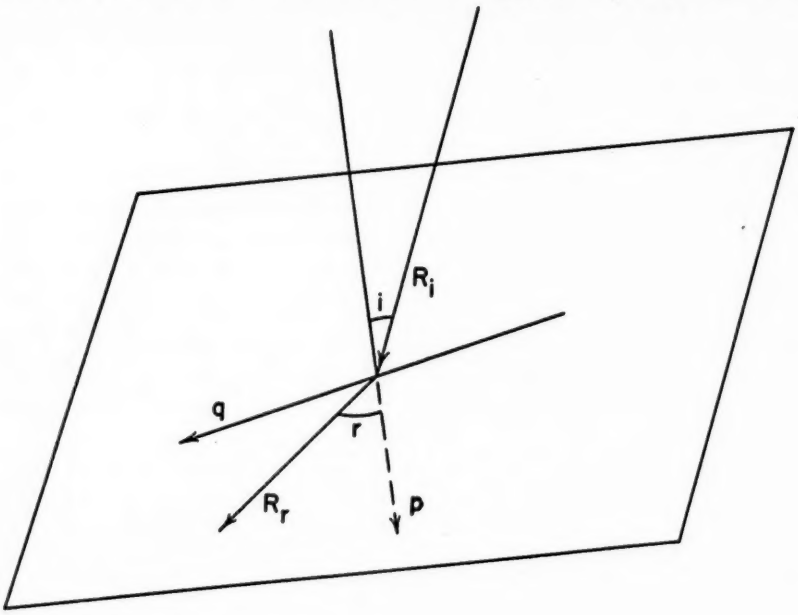

FIG. 2. The refracting plane in the vicinity of the point P. $\boldsymbol{R}_i$ is a unit vector in the direction of the incident ray, $\boldsymbol{R}_r$ a unit vector in the direction of the refracted ray, $\boldsymbol{p}$ the unit normal to the refracting plane, and $\boldsymbol{q}$ a unit vector in the line of intersection of the plane of wave propagation and the refracting plane.

is found from the refraction cross-sections. The scalar product of the unit vectors $\boldsymbol{R}_i$ and $\boldsymbol{p}$ gives

$$\begin{aligned} \boldsymbol{R}_i \cdot \boldsymbol{p} &= \cos i = \cos\alpha \cos l + \cos\beta \cos m + \cos\gamma \cos n \\ &= \frac{V_1}{\Delta x}(\Delta t_e \sin d_e + \Delta t_n \sin d_n) \\ &\quad + (\cos^2\theta_e - \sin^2\theta_n)^{1/2}(\cos^2 d_e - \sin^2 d_n)^{1/2}. \end{aligned} \tag{15}$$

The latter equation expresses the angle of incidence of the ray on the

refracting plane in terms of measured quantities and those derived directly therefrom.

The horizontal displacement of P from O is

$$\overline{OP''} = \overline{OP} \sin \gamma \tag{16}$$

and the direction of the projection P'' of P onto the datum plane is perpendicular to the apparent strike from O.

To find the direction cosines of the refracted ray we use Snell's law which says

$$V_2 \sin i = V_1 \sin r \tag{17}$$

and the following equations expressing the seismic ray unit vectors $\boldsymbol{R}_i$ and $\boldsymbol{R}_r$ in terms of $\boldsymbol{p}$, $\boldsymbol{q}$, the angle of incidence i, and the angle of refraction r:

$$\boldsymbol{R}_i = \boldsymbol{p} \cos i + \boldsymbol{q} \sin i \tag{18}$$

$$\boldsymbol{R}_r = \boldsymbol{p} \cos r + \boldsymbol{q} \sin r. \tag{19}$$

Eliminating the unknown unit vector $\boldsymbol{q}$ between these two equations, and applying Snell's law, the following equation for the refracted unit vector is obtained:

$$\boldsymbol{R}_r = \boldsymbol{p}\left(\cos r - \frac{V_2}{V_1} \cos i\right) + \frac{V_2}{V_1} \boldsymbol{R}_i. \tag{20}$$

Therefore, the direction cosines of the refracted ray are

$$\cos U = \left(\cos r - \frac{V_2}{V_1} \cos i\right) \cos l + \frac{V_2}{V_1} \cos \alpha \tag{21}$$

$$\cos V = \left(\cos r - \frac{V_2}{V_1} \cos i\right) \cos m + \frac{V_2}{V_1} \cos \beta \tag{22}$$

$$\cos W = \left(\cos r - \frac{V_2}{V_1} \cos i\right) \cos n + \frac{V_2}{V_1} \cos \gamma. \tag{23}$$

As before, the dip components, which we shall call D_e and D_n, of the reflector in the two cross-sections containing the refracted ray and the north and east lines respectively are related to the direction angles U and V of the refracted ray by the relations

$$D_e = U - 90° \tag{24}$$

$$D_n = V - 90° \tag{25}$$

where the usual convention regarding signs of dip components is maintained.

We are now ready to conclude the plotting of the strike and dip sign on the map of the datum plane.

Suppose the reflection time is t. Then, referring to Fig. 1, the time spent over the path OP and return will be

$$t_1 = 2\overline{OP}/V_1. \tag{26}$$

The time spent over the path PR and return will be

$$t_2 = t - t_1.$$

The distance $\overline{PR}$ is

$$\overline{PR} = V_2 t_2/2. \tag{27}$$

The horizontal offset distance of the strike-dip symbol from P'' is

$$\overline{R'P''} = \overline{PR} \sin W \tag{28}$$

where W is the resolved dip angle of the reflecting plane. The strike is easily found by the customary methods or by laying out the distance sec U on the I axis and sec V on the J axis (with due regard for signs). The two points thus determined are joined by a line which is parallel with the strike. Thus all quantities have been found from the data.

THE MULTILAYER PROBLEM

Eq. 20 may be applied reiteratively to tracing a ray through a succession of refracting interfaces to a reflector to find the strike and dip of such a reflector.

Fig. 3 is a schematic drawing of the path of a ray traveling through a succession of refracting media. The velocities in the successive media are $V_1, \cdots, V_n$, where the subscripts indicate the numerical order in which the media are traversed by the ray. $\boldsymbol{R}_n$ is the normal to the reflector and therefore completely defines its strike and dip.

Let:

$\boldsymbol{R}_s$ = a unit ray vector in the medium of the velocity V_s

$\boldsymbol{p}_s$ = a normal to the interface between the media of velocities V_s and V_{s+1}

i_s = angle of incidence of ray at said interface

r_{s+1} = angle of refraction at said interface

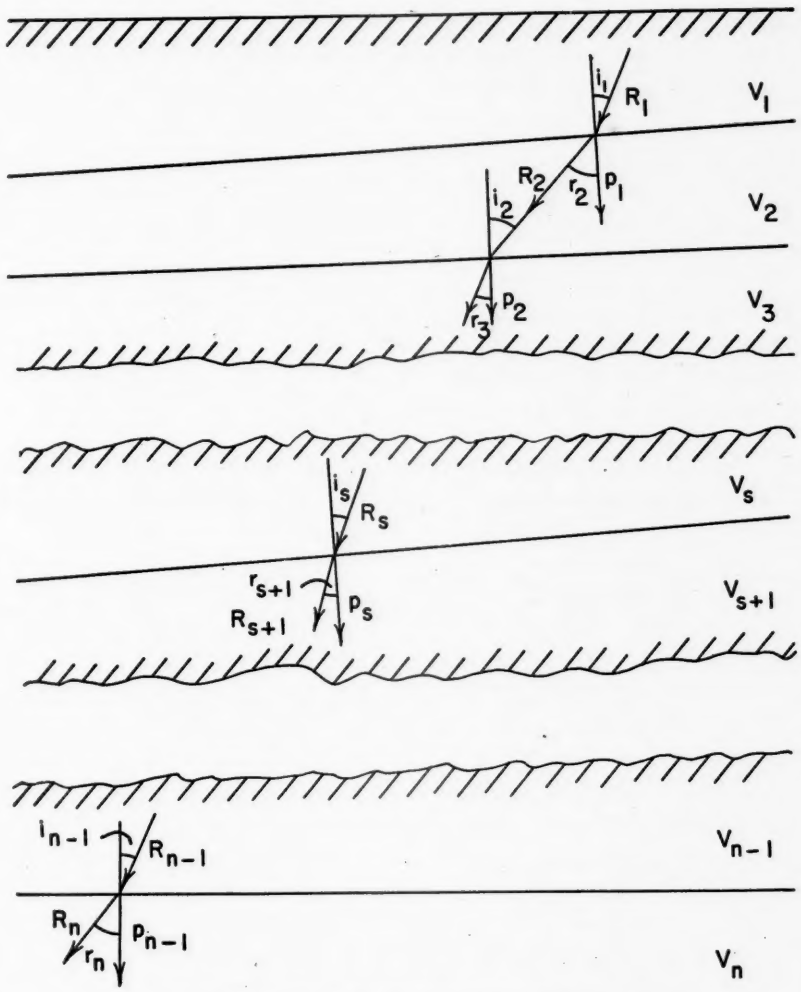

FIG. 3. Illustration of the physical set-up and the notation employed for the multilayer problem.

The unit vectors of the incident and refracted ray at an interface may be related by rewriting Eq. 20 as follows:

$$\frac{\boldsymbol{R}_{s+1}}{V_{s+1}} - \frac{\boldsymbol{R}_s}{V_s} = p_s\left(\frac{\cos r_{s+1}}{V_{s+1}} - \frac{\cos i_s}{V_s}\right). \tag{29}$$

This equation simply says that the vector difference of the wave slow-

ness of the refracted and incident waves equals the vector difference of the components of wave slowness along the normal to the interface.

We can write the identity:

$$\frac{\boldsymbol{R}_n}{V_n} - \frac{\boldsymbol{R}_1}{V_1} \equiv \sum_{s=1}^{n-1}\left(\frac{\boldsymbol{R}_{s+1}}{V_{s+1}} - \frac{\boldsymbol{R}_s}{V_s}\right). \tag{30}$$

Then substituting Eq. 29 in Eq. 30, we obtain

$$\frac{\boldsymbol{R}_n}{V_n} = \frac{\boldsymbol{R}_1}{V_1} + \sum_{s=1}^{n-1} \boldsymbol{p}_s\left(\frac{\cos r_{s+1}}{V_{s+1}} + \frac{\cos i_s}{V_{s+1}}\right). \tag{31}$$

When Eq. 31 is combined with Snell's law,

$$V_{s+1} \sin i_s = V_s \sin r_{s+1} \tag{32}$$

the unit ray vector or vector wave slowness in the nth medium may readily be determined. For example, the wave slowness in the fourth layer is given by the following expression:

$$\begin{aligned}\frac{\boldsymbol{R}_4}{V_4} = \frac{\boldsymbol{R}_1}{V_1} &+ \boldsymbol{p}_1\left(\frac{\cos r_2}{V_2} - \frac{\cos i_1}{V_1}\right) + \boldsymbol{p}_2\left(\frac{\cos r_3}{V_3} - \frac{\cos i_2}{V_2}\right) \\ &+ \boldsymbol{p}_3\left(\frac{\cos r_4}{V_4} - \frac{\cos i_3}{V_3}\right).\end{aligned} \tag{33}$$

In a numerical example the vector terms are computed in the order given in Eq. 33. Eq. 31 as illustrated by Eq. 33 states that the vector wave slowness in the last medium is equal to the vector wave slowness in the first medium plus the vector sum of the increments of wave slowness across the refracting interfaces encountered by the ray. The vector wave slowness thus computed for the nth medium determines the strike and dip of the reflector.

EXAMPLES

Table I shows the computations for two examples. In the first example the reflector has an apparent east component of dip of $+10°\ 15'$ (Column 4) and an apparent north component of dip of $+19°\ 30'$ (Column 5), as determined from the direction of arrival of the reflected wave. The upper section is assumed to have a velocity of 9000 ft./sec., and the lower section is assumed to have a velocity of 17,400 ft./sec. The shortest distance from the shot point to the interface ($\overline{OO'}$) is 1223 ft. The reflection time is 0.843 sec.

TABLE I

RESULTS OF THE COMPUTATION OF TWO EXAMPLES OF THE EFFECT OF AN UNCONFORMITY ON THE DETERMINATION OF THE LOCATION AND DIP OF A SEISMIC REFLECTOR

	1	2	3	4	5	6	7	8	9	10	11	12	
A *B* *C*	d_e $-\sin d_e$	d_n $-\sin d_n$	n $\cos n$	θ_e $-\sin\theta'$ $\sin d_e \sin\theta_e$	θ_n $-\sin\theta_n$ $\sin d_n \sin\theta_n$	γ $\cos\gamma$ $\cos n \cos\gamma$	$\cos i$ $\sin i$ $\sin r$ $\cos r$	V_2/V_1 $(V_2/V_1)\cos i$ *Q	$-(V_2/V_1)\sin\theta_e$ $-(V_2/V_1)\sin\theta_n$ $(V_2/V_1)\cos\gamma$	$-Q\sin d_e$ $-Q\sin d_n$ $+Q\cos n$	9+10 9+10 9+10	D_e D_n W	Dip direction Strike
I	+5° −.08716	0° 0	5° .99619	+10°15′ −.17794 +.01551	+19°30′ −.33381 0	22°16′ .92543 .92190	.93741 .34820 .67319 .73951	1.9333 1.8123 −1.0728	−.34402 −.64536 1.78916	.09351 .00000 −1.06871	−.25051 −.64536 +.72045	14°31′ 40°12′ 43°55′	N 21°12′E N111°12′E
II	−5° +.08716	0° 0	5° .99619	+10°15′ −.17794 −.01551	+19°30′ −.33381 0	22°16′ .92543 .92190	.90639 .42245 .81674 .57700	1.9333 1.7524 −1.1754	−.34402 −.64536 1.78916	−.10245 .00000 −1.17092	−.44647 −.64536 +.61824	26°31′ 40°12′ 51°49′	N 34°41′E N124°41′E
III	0° 0	+5° −.08716	5° .99619	+10°15′ −.17794 0	+19°30′ −.33381 +.02909	22°16′ .92543 .92190	.95099 .30929 .59796 .80150	1.9333 1.8386 −1.0371	−.34402 −.64536 1.78916	.00000 + .09039 −1.03315	−.34402 −.55497 +.75601	20°7′ 33°42′ 40°53′	N 31°50′E N121°50′E
IV	0° 0	−5° +.08716	5° .99619	+10°15′ −.17794 0	+19°30′ −.33381 −.02909	22°16′ .92543 .92190	.89281 .45040 .87077 .49166	1.9333 1.7261 −1.2344	−.34402 −.64536 1.78916	.00000 − .10759 −1.22970	−.34402 −.75295 +.55946	20°7′ 48°51′ 55°59′	N 24°36′E N114°36′E
V	0° 0	0° 0	0° 1.0000	+10°15′ −.17794 0	+19°30′ −.33381 0	22°16′ .92543 .92543	.92543 .37892 .73258 .68072	1.9333 1.7890 −1.1083	−.34402 −.64536 1.78916	.00000 .00000 −1.1083	−.34402 −.64536 +.68086	20°7′ 40°12′ 47° 5′	N 28° 5′E N118° 5′E
VI	5° −.08716	0° .0000	5° .99619	0° .0000 0	5° −.08716 0	5° .99619 .99239	.99239 .12302 .24604 .96923	2 1.98478 −1.01555	0 −.17432 1.99238	.08852 .00000 −1.01168	+.08852 −.17432 +.98070	− 5° 5′ +10° 2′ 11°16′	N 27°W N117°W

* $Q = \cos r - \frac{V_2}{V_1}\cos i.$

For this fixed apparent reflector dip we have assumed five different dips for the refracting interface, namely: (I), 5° east; (II), 5° west; (III), 5° north; (IV), 5° south; (V) level. For each of these five cases

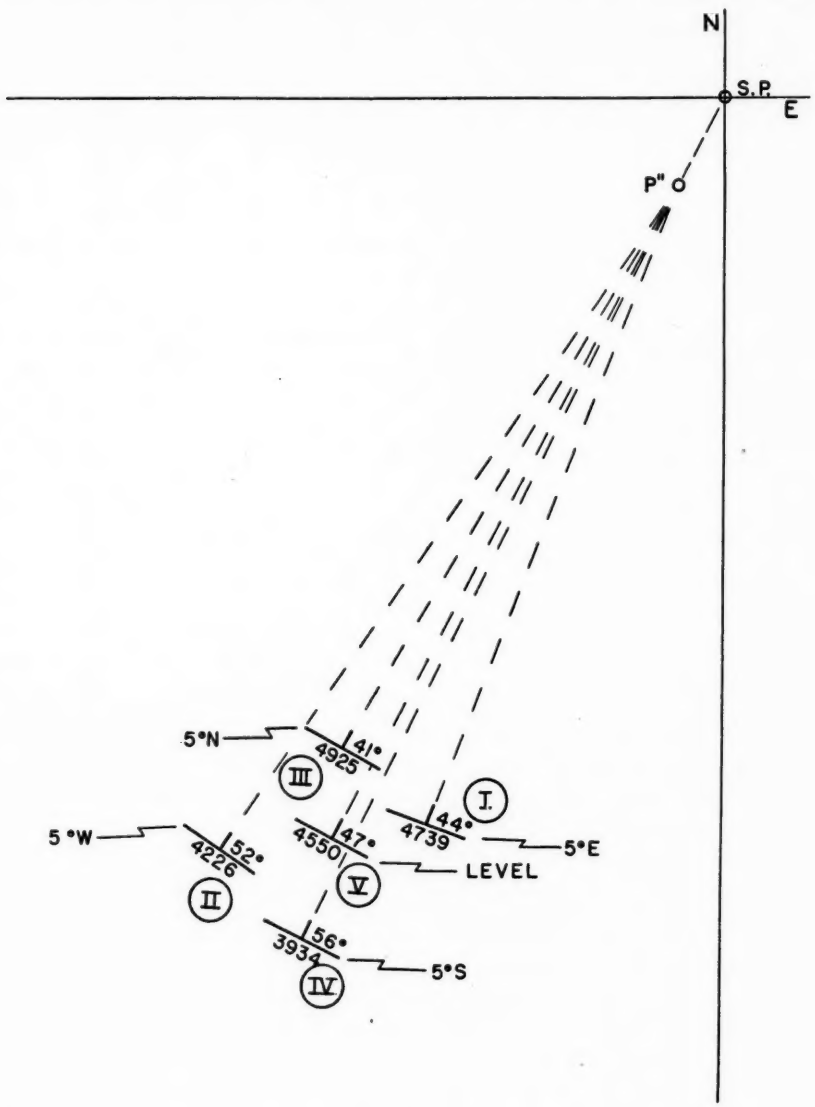

FIG. 4. Value of dip and strike, direction, distance, and depth of reflection point, as influenced by five choices of the direction of dip of the unconformity.

the resolved dip, W, the dip direction, and the strike are computed as shown in the table.

In addition, the positions of the strike-dip symbols and the corresponding depths are computed (not included) and plotted in Fig. 4.

This example was taken from an actual case showing the given apparent dip. In this case the total variation of dip for $\pm 5°$ dip change in the refracting interface is $15°$ and the corresponding change in depth is nearly a thousand feet. In the actual case the dip of the interface was larger than $5°$ so the correction was even more important than indicated by this example.

The second example is shown in rows VI of the table. Here the apparent dip of the reflector is $5°$ north and the dip of the refractor is $5°$ east. The velocity in the lower medium is twice that in the upper. It will be observed that the dip direction is rotated $27°$ west by the dip of the refracting interface.

Of course the latter example merely illustrates the fact that for small dips the strike direction may be seriously influenced by the dip and strike of even a slightly dipping refracting interface.

CONCLUSION

The effects of changes of dip and strike *within* the geological section studied, may, in some cases, be of practical significance in computing the strike and dip of a reflector beneath the section. This has been emphasized in more than one area investigated. We have seen two areas where failure to take account of such effects yields a random assortment of apparently unrelated dips, whereas computations based on methods presented in this paper make it possible to unify all data as a consistent whole.

There is no need to emphasize the fact that it is more difficult to relate a semi-random assortment of data than it is to relate a unified set of data, and that the relative dependabilities of the two kinds of data are vastly different. In some cases there is positive evidence that the oversimplified interpretation gives an essentially incorrect picture. In other cases the result will be clouded by doubt. The methods discussed here are definitely helpful in clearing up some sets of apparently inconsistent data.

We are convinced that the present method constitutes a definite forward step, but would guard against its application without (a) a full understanding of the assumptions involved, (b) a considered estimate of the probable degree of variation of actual conditions from hypo-

thetical conditions, and (c) a partial understanding of probable effects due to failure of the hypothetical conditions to correspond to the facts. When these factors are considered, the results of the application of the method will furnish some information regarding the above estimate, (b). This estimate, of course, may constitute a significant contribution to the sum of all the information obtainable in a particular area.

A RAPID METHOD FOR MEASURING THE PROFILE COMPONENTS OF HORIZONTAL AND VERTICAL GRAVITY GRADIENTS*

C. A. HEILAND†

ABSTRACT

The trend in gravity exploration in the past years indicates the rather remarkable fact that a method of low resolving power (the gravity meter) has replaced one of higher resolving power (the torsion balance). This is entirely due to the superior speed of the former and suggests an instrument and procedure in which observation time is reduced by (1) reduction in number of quantities measured; (2) use of a reference direction near that of the maximum effect; (3) elimination of the torsionless position as unknown; (4) reduction in period, with compensating increase in optical sensitivity; (5) stabilization of thermal conditions. These objectives are attained by (1) measuring the profile components of gradients and curvature values, preferably at right angles to the assumed strike; whereby, for an ideal two-dimensional feature, also the vertical gravity gradient is obtained, and the vertical and horizontal gravity components may be calculated by integration; (2) by holding the torsionless position constant with temperature control; (3) by decreasing the period and observation time to 3–4 minutes, and (4) by using a beam arrangement which will give the gradient in only one azimuth, and the profile gradient of the horizontal gravity component in a second azimuth if desired. Latitude and terrain corrections are also somewhat simplified by the proposed procedure.

INTRODUCTION

Gravimetric exploration methods have followed a characteristic trend of evolution which differs in several respects from that of other geophysical methods. While elsewhere the tendency has been toward an increase in resolving power, the trend in gravitational methods has, in the past years, been virtually in the opposite direction. It will be useful to consider briefly the causes of this situation to afford a better understanding of the method described herein.

Before proceeding further, it is well to review briefly the quantities occurring in gravitational exploration, which are summarized in Table I.

EVOLUTION OF GRAVIMETRIC EXPLORATION

Gravimetric methods fall into two major groups: (1) those in which the gravity force itself is measured, as by means of the gravity pendulum and the gravity meter; and (2) methods for determining the rate of change of gravity in space; the better known instruments utilized are (a) the Eötvös torsion balance for the measurement of horizontal

* Presented at the annual meeting, April, 1942, Denver, Colorado.

† Colorado School of Mines, Golden, Colorado.

gravity gradients, and (b) instruments designed to determine the vertical gradient of gravity. Measuring a derived quantity, the second group of methods may be said to have a greater resolving power than the first.

Now it is noteworthy that at the early beginning of geophysical exploration, the method of greater resolving power was introduced first. R. v. Eötvös, having invented the torsion balance in 1886, ap-

TABLE I

DEFINITIONS OF QUANTITIES USED IN GRAVITATIONAL EXPLORATION

	North (x)	*East* (y)	*Vertical* (z)
Gravity Components:	$\frac{\partial U^*}{\partial x} = g_x$	$\frac{\partial U}{\partial y} = g_y$	$\frac{\partial U}{\partial z} = g_z$
Total Gravity:	$\sqrt{g_x^2 + g_y^2 + g_z^2} = g \approx \frac{\partial U}{\partial z} = g_z$		
Gradients of the vertical component:	$\frac{\partial^2 U}{\partial x \partial z} \equiv U_{xz} \approx \frac{\partial g}{\partial x}$ (horizontal gravity gradients)	$\frac{\partial^2 U}{\partial y \partial z} \equiv U_{yz} \approx \frac{\partial g}{\partial y}$	$\frac{\partial^2 U}{\partial z^2} \equiv U_{zz} \approx \frac{\partial g}{\partial z}$ (vertical gravity gradient)
Gradients of the horizontal component:	$\frac{\partial^2 U}{\partial x^2} \equiv U_{xx} = \frac{\partial g_x}{\partial x}$	$\frac{\partial^2 U}{\partial y^2} \equiv U_{yy} = \frac{\partial g_y}{\partial y}$	—
	$\frac{\partial^2 U}{\partial x \partial y} \equiv U_{xy} = \frac{\partial g_y}{\partial x}$	$\frac{\partial^2 U}{\partial y \partial x} \equiv U_{xy} = \frac{\partial g_x}{\partial y}$	—
Curvature values:	$\frac{\partial^2 U}{\partial y^2} - \frac{\partial^2 U}{\partial x^2} \equiv U_\Delta$		

* U is the combined potential of attraction and centrifugal force.

plied it in 1915, upon the suggestion of Hugo von Boeckh, in a survey of oil structure. Up to the introduction of the gravity meter, the torsion balance retained first place in gravimetric exploration for a period of some twenty years.

Early attempts to use direct measurements of gravity in exploration have not been lacking. The parallelism of gravity anomalies and regional geologic structure was observed by Deecke as early as 1907. Although considerable improvements were made in the speed and ac-

curacy of pendulum observations, the method was unable to compete successfully with the torsion balance. Up to about 1935, direct gravity measurements played but a secondary role and were used principally for the mapping of regional structural features.

With the introduction of the gravity meter, the situation changed, and a method of inferior resolving power replaced one of higher resolution. Fig. 1 gives a graphical picture of this development.[1] It shows that in about five years' time the torsion balance declined in the Gulf

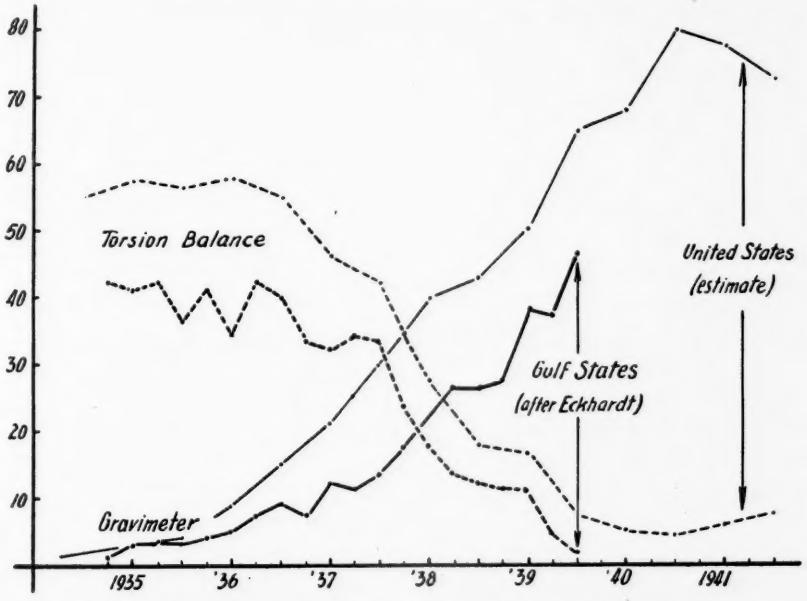

FIG. 1. Torsion balance and gravimeter parties operating in the United States, 1934–41.

Coast from forty to a very few parties, whereas, in the same time interval, the gravity meter expanded to as many parties as the torsion balance had prior to the introduction of the gravity meter. At this writing, the number of gravity meter parties in the United States is close to eighty with the torsion balance apparently very much "in the dog house."

RESOLVING POWER OF GRAVITY METER AND TORSION BALANCE

The speed of the gravity meter makes it an ideal reconnaissance instrument. Yet there is a definite feeling on the part of some opera-

[1] E. A. Eckhardt. *The Explosives Engineer*. April, 1940, p. 104.

tors that it is not entirely suitable for all gravimetric problems, that it lacks something, and is inferior in geologic definition for an appreciable number of applications. A situation of this kind is illustrated in Fig. 2, showing a deep-seated fault in limestone against shale at a depth of 2000 feet with a displacement of 1000 feet. It is seen that the gravimeter, giving the relative gravity Δg, indicates this abrupt subsurface density discontinuity only by a gradual rise in the gravity. Conversely, the torsion balance, giving the gravity gradient, or $\partial g/\partial x$,

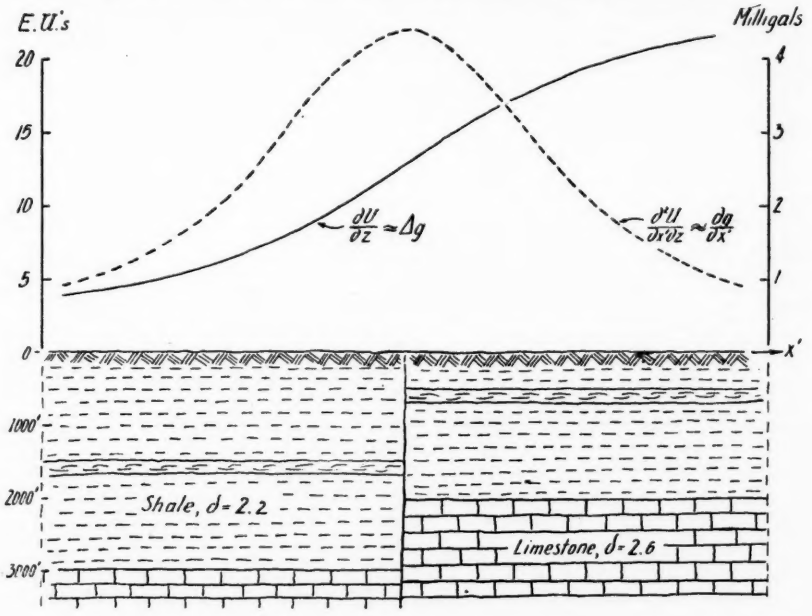

FIG. 2. Illustrating a difference in resolving power between the gravimeter and torsion balance, for the case of a fault. Solid curve represents gravity, dashed curved horizontal gradient of gravity.

indicates the fault by a definite maximum directly above the trace of the fault and is thus superior to the gravity meter when applied to a problem of this kind.

It is evident that the reason for the discontinuance of the torsion balance in favor of the gravity meter (i.e., a method of lower resolving power) is entirely due to the superior speed of the latter. Attempts have not been lacking to increase the operating speed of torsion balances by the adoption of special beam designs and by a reduction of size and weight. Yet, it must be admitted that during the fifty years

which have elapsed since its invention, there has been no fundamental change in design or operating principle, which, incidentally, testifies to the ingenuity and thoroughness with which Eötvös worked out his invention.

TORSION BALANCE OBSERVATION TIME

There are several good reasons why it takes such a long time to read a torsion balance. First, the instrument measures two parameters of the gravitational field, commonly known as gradients and curvature values, instead of one. Second, contrarily to gravity whose vertical direction is fixed by agreement, the orientation of the gradient and curvature vectors must be determined from their components in the astronomic directions, necessitating a determination of four quantities. Third, the torsionless position of the beam is treated as an unknown quantity whereby, for two beams, the number of unknowns is raised to six. Fourth, the conventional optical system of moderate magnification necessitates a comparatively large mechanical sensitivity which, in turn, gives rise to a long period. Deviations from thermal equilibrium in the interior of the instrument make it necessary to repeat at least one, if not two, sets of readings, whereby the observation time is increased further.

MEANS OF REDUCING TORSION BALANCE OBSERVATION TIME

It is possible to reduce the observation time of a torsion balance without sacrificing significant accuracy. Consideration of the factors enumerated in the preceding paragraph shows that this can be done most effectively by a combination of the following means: (1) reduction in the number of quantities measured; (2) establishment of a single reference direction at or near that of the maximum effect, as in gravity measurements; (3) elimination of the torsionless position as an unknown quantity; (4) reduction in mechanical sensitivity and period with a compensating increase in optical magnification; (5) stabilization of thermal conditions by thermostat control. Some of these measures are effective in more than one respect; establishing a single reference direction, for instance, reduces the number of quantities to be measured; thermal control reduces the drift of the torsionless position, etc.

GRADIENTS VS. CURVATURES

The possibility of reducing the number of quantities measured in a torsion balance calls to mind the often debated question whether it

would not be best to eliminate the curvatures altogether. It is quite true that in many areas the curvatures are erratic and contribute nothing to the geophysical picture. Even where they show a regular trend, the tendency of most interpreters is to utilize the gradients alone and to be satisfied if qualitatively the curvatures confirm the gradient picture. Furthermore, the gradients lend themselves more readily to qualitative interpretation since by graphical integration

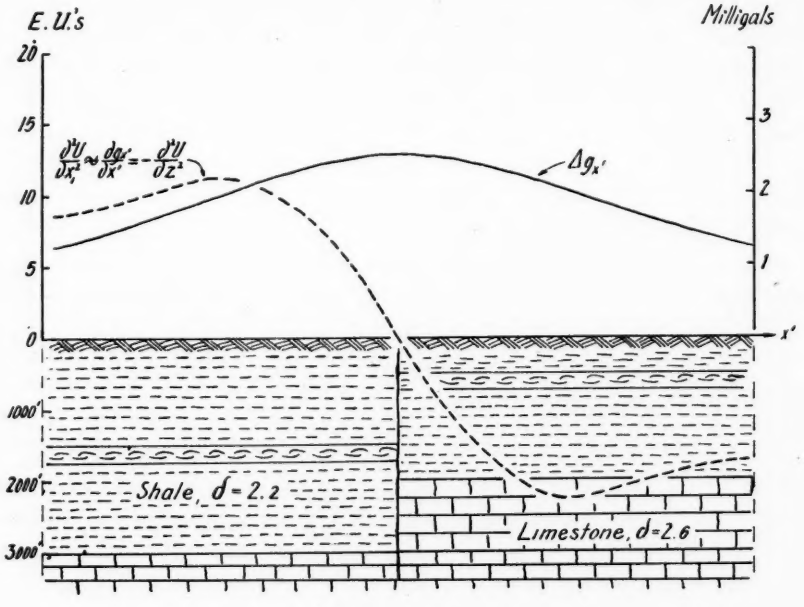

FIG. 3. Illustrating the integration of a curvature profile into a profile of horizontal component of gravity, for a two-dimensional geologic feature (fault).

they may be converted without great difficulty into gravity anomalies that may, in turn, be plotted as an isogal map.

It is usually overlooked, however, that by the same process of integration, the curvature values may also be converted into horizontal gravity components. For two-dimensional geologic features, the horizontal gradient of the horizontal component of gravity may be converted by integration into a curve, giving the variation of the horizontal gravity component, as is illustrated in Fig. 3. Furthermore,

for two-dimensional features, the gradient of the horizontal gravity component is also equal to the negative vertical gravity gradient. This gives the curvature value added geological significance as is evident from Fig. 3.

The general preference for the gradient has led to construction of torsion balance beams which do not respond to the curvatures and merely indicate the gradients. It is questionable whether this is a good approach to the problem. A better and more flexible design is one that provides for the measurement of the gradients in one position and yields the curvatures by a second position if the operator is willing to spend more time in obtaining the added information. In other words, the design should make possible *separate* measurements for the two components like a combination vertical and horizontal magnetometer. For rapid magnetic reconnaissance we would select the vertical component; for more detail, also the horizontal component would be observed. Application of the same principle would be useful in gravimetric exploration. The instrument and method described herein makes possible the measurement of the gradient in one position and yields the curvature value by observation in a second position.

ADVANTAGES OF A DIFFERENT REFERENCE DIRECTION FOR GRADIENTS AND CURVATURES

In the conventional torsion balance procedure, the direction of the resultant or maximum gradient, and maximum or minimum curvature, is established by measuring the components in the meridian and prime vertical. For geologic bodies that are extended in the direction of strike, the maximum and minimum gradient and curvature values are located in a direction at right angles to the strike. Proceeding, therefore, somewhat analogously as we do in measuring gravity by observing the attraction in or near the direction of maximum effect, it is evident that the necessity for obtaining the gradient and curvature vectors from two components may be eliminated by orienting the instrument with reference to the strike. In many instances, the strike direction is known with accuracy. Profiles may then be run at right angles to the strike, and all quantities measured may be referred to this direction. If y' be designated as the strike direction, and x' as the direction normal thereto, then the following relations prevail for an ideal two-dimensional geologic body:

$$\left.\begin{aligned} \frac{\partial g}{\partial y'} &\equiv U_{y'z} = 0 \\ \frac{\partial^2 U}{\partial x' \partial y'} &\equiv U_{x'y'} = 0 \\ \frac{\partial^2 U}{\partial y'^2} &\equiv U_{y'y'} = 0 \\ \frac{\partial^2 U}{\partial x'^2} &\equiv -\, U_{\Delta}'. \text{ Also,} \\ \frac{\partial^2 U}{\partial x'^2} &= -\,\frac{\partial^2 U}{\partial z^2} \equiv -\, U_{zz}. \end{aligned}\right\} \quad (1)$$

If the profile direction deviates from that normal to the strike, the components referred to above are not quite zero. This, however, is not objectionable as long as it is understood that $U_{x'z}$ and $U_{x'x'}$ then refer merely to the profile components and not the maximum values. The instrument and method described herein are, therefore, designated as being intended for the measurement of the *profile* components of the horizontal and vertical gravity gradients from which, by integration, the horizontal and vertical components of gravity may be derived.

ELIMINATION OF TORSIONLESS POSITION AS AN UNKNOWN QUANTITY

In evaluating torsion balance records, it is customary to calculate the torsionless position by forming the average of successive deflections in the order 1, 2, 3; 2, 3, 1; 3, 1, 2; etc. There is no reason to follow this procedure in an instrument designed for the measurement of gradients and curvatures in one position only. Such an instrument utilizes a relative procedure by measuring *changes* in deflection from one place to another; variations in the zero position may be detected by base ties, if necessary. Furthermore, the zero or torsionless position may be held constant by temperature control. It is not even necessary for this position to correspond to zero beam deflection; a normal or latitude effect will usually be present, its magnitude depending on the beam orientation. This will remain constant throughout a straight profile and no adverse effect results as long as the deflection remains reasonably constant or shows a linear drift. It is evident, therefore, that the measurement of gradients and curvatures may be reduced to a determination of *one* quantity each.

REDUCTION OF BEAM PERIOD

Observations with the conventional type of torsion balance having a beam period of twenty minutes take about one and one-half hours since three regular and one repeat-observation are required. The observation time may be reduced to three minutes for gradients alone, and to six to seven minutes for both gradients and curvatures, by using the beam orientations referred to before, and by reducing the mechanical sensitivity of the beam. In comparison with the conventional beam of 20 minutes natural period, this necessitates a compensating increase of the optical sensitivity by 50 times since the mechanical sensitivity is proportional to the square of the period. The increase in optical sensitivity is accomplished in the instrument described below by increasing the optical lever and providing for multiple reflection. Contrarily to the conventional balance, the beam deflections are not measured directly but the beam is returned at each station to a zero position by the use of an auxiliary torsion wire operated from a second torsion-head. In comparison with the conventional arrangement, the beam is highly damped, allowing it to come to rest without overshoot.

STABILIZATION OF ZERO-POSITION BY THERMAL CONTROL

Because of the small magnitude of the forces under measurement, the suspension in an Eötvös torsion balance is protected from thermal disturbances by three metal envelopes. Despite this precaution, there is generally a more or less pronounced variation of beam-position with temperature. To begin with, this is occasioned by a direct effect of temperature on the wire; secondly, the beam is shifted by air currents set up in the interior of the instrument by thermal differences between the upper and lower portions of the instrument. To minimize the latter, it is customary to adjust the transverse position of the beam in the inner case in such manner that this effect is a minimum. In view of the favorable results which have been attained in gravimeters with temperature control, it is evident that both the effect of temperature variations on the wire as well as that of temperature gradients on the beam itself, can be eliminated simultaneously by controlling the temperature in the chamber surrounding the beam. It is not even necessary to control the temperature as accurately as it is done in a gravimeter.

BEAM ARRANGEMENT IN THE NEW INSTRUMENT

It was stated before that a reduction in the number of quantities customarily observed with the torsion balance is possible by suitable

orientation with respect to the geologic feature under survey. However, this alone does not attain the objective of producing an instrument which will indicate the most significant quantity (the gravity gradient) in *one* position of the instrument. A beam combination is required which deviates from the conventional arrangement. In the standard form of the Eötvös torsion balance, two beams are arranged side by side in antiparallel arrangement. Both beams are of the gradient type; that is, one end carries a weight in one level, and the other end carries a weight at a different level. Hence, each beam is affected by the curvature values in addition to the gradients, as will be seen by reference to Eq. 2.

For this reason, a deviation from the standard arrangement is required. When a gradient-beam is oriented parallel with the direction of the strike of a two-dimensional body, it is theoretically affected only by the gravity gradient at right angles to the strike since the $U_{x'y'}$ component of the curvature is zero. In practice, however, that is not always the case, nor is the profile always at right angles to the strike. Therefore, if the beam is arranged at right angles to the *profile*, it will be affected by both the gradient component and the curvature components in the direction of the profile. It would, of course, be possible to make measurements in various beam positions to eliminate the curvature values, but that is not the ultimate objective of the method here described. Its purpose is to determine gradients alone in *one* position of the instrument. Therefore, in addition to the conventional gradient beam, a curvature beam is provided (Fig. 4) so that the *difference* of the deflections of the gradient beam and the curvature beam gives the gradient alone or rather, the gradient component in the direction of the profile. Then, if it is desired to also measure the curvature value in the direction of the profile, the entire assembly is turned into a direction 45 degrees off the profile. For a strictly two-dimensional feature, this will give the profile gradient of the north component of gravity which, by application of Laplace's relation, is identical with the negative vertical gravity gradient.

THEORY

In the azimuth α from north, the deflection n of a torsion balance beam in which the weights are in different levels, is given by the relation

$$n = \boldsymbol{a}(U_{\Delta} \sin 2\alpha + 2U_{xy} \cos 2\alpha) + \boldsymbol{b}(U_{yz} \cos \alpha - U_{xz} \sin \alpha) \qquad (2)$$

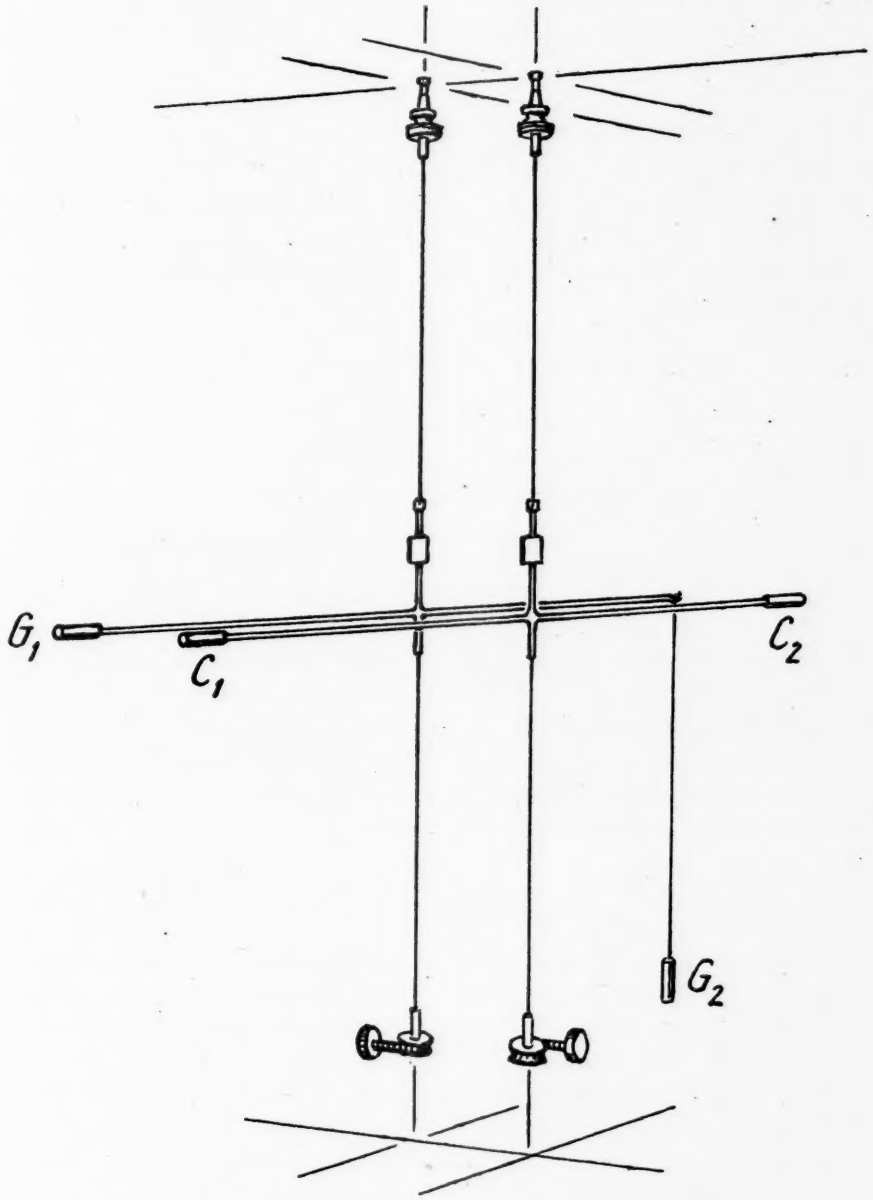

FIG. 4. Beam arrangement of the new instrument. G_1–G_2 is the gradient beam, C_1–C_2 the curvature beam.

where a and b are instrument constants which are dependent only on the beam dimensions and the optical system, and are given by

$$a = \frac{fK}{\tau} \quad \text{and} \quad b = \frac{2fmlh}{\tau} \tag{3}$$

in which f is the focal length of the lens in front of the beam mirror, K is the moment of inertia of the beam, m the mass attached to each end of the beam, $2l$ the beam length, h the vertical distance of the two masses at the ends of the beam, and τ the torsional coefficient of the suspension wire.

Assume now that measurements are made along a traverse line the direction of which is x', whereas the direction at right angles thereto is y'. Then, α' is the azimuth with respect to the profile direction, and the primed gravity gradient and curvature values apply to the profile direction and the prime vertical thereto. Thus, Eq. 2 is for the new directions:

$$n' = a(U_\Delta' \sin 2\alpha' + 2U_{x'y'} \cos 2\alpha') + b(U_{y'z} \cos \alpha' - U_{x'z} \sin \alpha') \tag{4}$$

The profile will be laid out, if at all possible, at right angles to the strike. It is assumed, of course, that regardless of the actual disposition of the field stations, the orientation of the instrument relative to an *average* profile direction will be maintained which, in most areas, can be readily done by means of the compass attached to the instrument. If, then, *two beams* are provided, one with weights in *different* levels (subscript 1) and the other with weights in the *same* level (subscript 2), Eq. 4 may be written for the two beams:

$$\left.\begin{aligned} n_1 &= a_1(U_\Delta' \sin 2\alpha' + 2U_{x'y'} \cos 2\alpha') + b(U_{y'z} \cos \alpha' - U_{x'z} \sin \alpha') \\ n_2 &= a_2(U_\Delta' \sin 2\alpha' + 2U_{x'y'} \cos 2\alpha') \end{aligned}\right\}. \tag{5}$$

By making the two beams of the same length and by using suspension wires of identical characteristics, their response to the curvatures may be made identical. With this in mind, the subscripts of the "a" constant may be dropped.

To obtain the gravity gradients in one position only (which would require *three positions* in the conventional types), the instrument is oriented at right angles to the profile direction at every station. Then $\alpha' = \pi/2$ and

$$\left.\begin{aligned} n_1 &= -2aU_{x'y'} - bU_{x'z} \\ n_2 &= -2aU_{x'y'} \end{aligned}\right\}. \tag{6}$$

The deflections of both beams are read in this position and their *difference* taken so that

$$n_2 - n_1 = b \cdot U_{x'z}. \tag{7}$$

It is seen, therefore, that for the determination of the profile component of gravity gradients, only one position and, therefore, only about 3 minutes observation-time are required. The effect of curvature cancels by using the method described. In the case of an ideal two-dimensional geologic feature, the curvature $U_{x'y'}$ is zero; therefore, the deflection of the second beam may, in practice, be assumed to be reasonably small. It is evident, however, that if the curvature is not zero, the accuracy of the observation will be dependent on the constancy of *two* reference (or so-called torsionless) positions of the beam.

If it is desired to determine the curvature values *in addition* to the gradients, the instrument is then rotated into a direction 45 degrees off the profile and only the *second* beam is read. Then, since $\alpha' = 45°$,

$$n_2 = aU_{\Delta}'. \tag{8}$$

For an ideal two-dimensional geologic feature with a profile at right angles to the strike, U_{Δ}', in accordance with Eq. 1, is $-\partial^2 U/\partial x_1^2$ and, therefore, represents the gradient of the horizontal gravity component at right angles to the strike. Further, since the latitude variation can be corrected for, whereby the effect of the centrifugal force is eliminated, Laplace's Law applies in the form

$$\frac{\partial^2 U}{\partial x'^2} + \frac{\partial^2 U}{\partial y'^2} + \frac{\partial^2 U}{\partial z^2} = 0. \tag{9}$$

Since the y'-gradient of the y'-component of gravity is zero for an ideal two-dimensional geologic feature, it follows that the deflection of the second beam will give directly the vertical gravity gradient in such case. It may be mentioned in passing that it would be possible to make an instrument permitting of measuring the gravity gradient and the curvature value in *one* position if the $U_{x'y'}$ component were zero, as is the case for the ideal two-dimensional structure. Such an instrument would have a gradient beam, and a curvature beam making an angle of 45 degrees with the gradient beam. Then, if the gradient beam is at right angles to the profile or strike, the curvature beam would make an angle of 45 degrees with the strike, so that the gravity gradient and the $U_{x'x'}$ components could be read from each beam in one instrument position.

DESIGN OF INSTRUMENT

Following is a description of a proposed instrument design with dimensions required to attain the necessary sensitivity.

The general design resembles that of a conventional torsion balance. The gradient and curvature beams are mounted in separate tubular chambers. The torsion wires of the main suspension are short and have a torsion coefficient of 18. Contrary to the conventional balance, the reading devices are arranged transversally relative to the beams instead of longitudinally. The telescopes are on top of the case. The length of the optical lever, by reflection on a stationary mirror, is 85 centimeters. The auxiliary torsion wires are fastened to the lower centers of the beams. Readings on the external dials are taken by returning the beams to their zero positions. The necessary sensitivity of the optical system is attained by multiple reflection on the cover glass in front of the balance beam mirror, the sixth image giving sufficient precision. The beam lengths are 30 centimeters, the masses at the ends of the beams are 40 grams each, the distance between the upper and lower weights on the gradient beam is 30 centimeters, and the moment of inertia of each beam is 18,000 CGS units. The beams are damped electromagnetically. The beam chambers are surrounded completely by heating coils, operated from a storage battery-controlled thermostat that maintains the temperature to an accuracy of 0.02 degree F. The periods of the beams are 3 minutes each. Since the telescopes are essentially scale-magnifiers, permitting an accuracy of 1/100 of a millimeter in the determination of the deviation from the zero position, the optical lever is 85,000 scale units which gives sufficient accuracy for measuring beam-deflections to 1 Eötvös Unit. The whole instrument may be rotated on its base and may thus be oriented by means of a compass or a sighting attachment on the top with respect to a distant object or relative to the magnetic meridian.

CORRECTIONS

Corrections are necessary for (1) latitude variations of the profile components of gradients and curvatures; (2) for terrain.

The latitude correction on the profile-component of the gradient is given by

$$(U_{x'z})_{\text{lat.}} = 8.16 \cdot 10^{-9} \sin 2\phi \cos \beta \qquad (10)$$

where β is the angle of the profile with astronomic north. Similarly, the correction on the curvature is

$$(U_{\Delta'})_{\text{lat.}} = 5.15 \cdot 10^{-9}(1 + \cos 2\phi) \cos 2\beta. \qquad (11)$$

The value of these corrections for astronomic north may also be taken from the diagram Fig. 7-73a, p. 211, of *Geophysical Exploration*,[2] and may be projected graphically upon the profile direction as shown in Fig. 7-93, p. 246.

The observation of profile components, as proposed in this paper, means a considerable simplification in terrain correction. Although it is still necessary to survey the terrain in the same number of directions as in the conventional method, the calculation is cut in half when both gradients and curvatures are observed. Only one-fourth of the customary calculation is required when gradients alone are wanted. With this restriction, field observations of elevations may be reduced to six azimuths.

The terrain grids are no longer laid out in astronomic directions but in respect to the profile direction. Measurements are made as usual on a selected number of circles.[3] If the elevation h in the direction of the profile is indicated by the subscript 1, the terrain correction, as calculated by Schweydar's first method, becomes for the gradient:

$$(U_{x'z})_{\text{terrain}} = \frac{\delta}{8} \sum_{1}^{n} k_n[0.707(h_2 - h_4 - h_6 + h_8) + h_1 - h_5], \quad (12)$$

in which δ is the density. Likewise, for the curvature value (if observed):

$$(U_{\Delta}')_{\text{terrain}} = \frac{\delta}{8} \sum_{1}^{n} k_n(h_1 - h_3 + h_5 - h_7). \qquad (13)$$

The summation is extended over as many of the following n circles with the ring constant k_n as may be required: 1.5, 3, 5, 10, 20, 30, 40, 50, 70, and 100 meters. In fairly level terrain, calculation to 20 meters usually suffices.

[2] New York, Prentice-Hall, 1940.
[3] For details see *Geophysical Exploration*, pp. 220–223.

NOMOGRAMS FOR COMPUTING TIDAL GRAVITY*

THOMAS A. ELKINS†

ABSTRACT

It is possible, by the use of a nomogram devised by Dr. James B. Friauf (*Journal of the Franklin Institute*, Vol. 232, pp. 151–174, 1941) for the solution of spherical triangles, to make simple nomograms for the computation of tidal gravity. Two types of such nomograms are explained and illustrated. The first is for computations at a fixed latitude on the earth; the second is for computations at a fixed point. With the second type the computation of tidal gravity is reduced to a simple routine matter, especially if *The American Air Almanac* is used as the source of the astronomical data needed. The accuracy of these nomograms is studied and a comparison is made of this new method with that recently devised by Dr. Adler (GEOPHYSICS, Vol. 7, pp. 35–44, 1942).

INTRODUCTION

There has lately been a marked increase in interest in the subject of tidal gravity corrections in relation to gravimeter surveys, as is evidenced by a recent paper of Adler (Adler, 1942)‡ in which he describes a chart method of computing the tidal gravity. The purpose of the present paper is to describe a nomogram method of computing tidal gravity which may be used to make the calculation a simple routine matter.

TIDAL GRAVITY THEORY

By tidal gravity at a point on the surface of the earth we shall mean the vertical component (i.e., along the outward normal) of the tide-producing force at that point. Then it is well known (Schureman, 1924, page 20) that the tidal gravity, G, due to a single celestial body, such as the sun or the moon, is to a good approximation,

$$G = \frac{3\gamma Ma}{D^3}(\cos^2\theta - \tfrac{1}{3}) = 3g\frac{Ma^3}{ED^3}(\cos^2\theta - \tfrac{1}{3}),$$

where M is the mass of the celestial body,

E is the mass of the earth,

D is the distance between the centers of the celestial body and of the earth,

* Manuscript received for publication November 9, 1942. Presented before the Allegheny Mountain Section of the Mathematical Association of America, April 25, 1942, Pittsburgh, Pa., under the title, "Nomograms for tidal corrections of gravity."

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‡ References in this form are to the list at the end of this paper.

a is the mean radius of the earth,
γ is the gravitational constant,
g is the mean value of gravity on the earth's surface, defined as $\gamma E/a^2$, and
θ is the geocentric zenith distance of the celestial body at the point for which the tidal gravity is being computed.

In this formula, the tidal gravity is taken positive in the direction of the outward normal. This should be remembered when this formula or the nomograms derived from it are used to correct gravity values observed with the gravimeter, for which the positive direction is ordinarily taken opposite to that assumed above.

For the moon, the term before the quantity in parentheses is 16.485, and for the sun, 7.610, when the gravity unit is 0.01 milligal and mean values are used for the two central distances to moon or sun. In the evaluation of these terms we have taken γ as 6.670×10^{-8} c.g.s. units (Birch, 1942, page 104), E as 5.98×10^{27} gms. (Baker, 1938, page 93), and the remaining values needed as in Schureman's Table 2 (Schureman, 1924, page 173).

From the formula for G it follows that the tidal gravity caused by either the sun or the moon depends on only two variable quantities, D and θ. We shall first consider the variation of D. For the sun the variation in tidal gravity because of change in the sun's distance from its mean value will not be more than six per cent. Since the average effect of the sun is less than half that of the moon, we shall not bother correcting for the change in distance. The variation in tidal gravity because of change in the moon's distance is considerable, as is shown in Table I, which lists the correction factor by which the lunar tidal gravity must be multiplied when the horizontal parallax of the moon (which is a measure of its distance) has a value other than its mean value, which is taken here to be 57′.

TABLE I

CORRECTION FACTOR FOR TIDAL GRAVITY DUE TO CHANGE IN THE MOON'S DISTANCE

Horizontal Parallax	*Correction Factor*
54′	0.85
55	0.90
56	0.95
57	1.00
58	1.05
59	1.11
60	1.17
61	1.23
62	1.29

We next consider the variation of θ. From spherical trigonometry it easily follows that

$$\cos^2 \theta = (\cos \delta \cos \phi \cos \lambda + \sin \delta \sin \phi)^2,$$

where δ is the declination of the celestial body,

λ is its local hour angle at the point for which the tidal gravity is being computed, and

ϕ is the latitude of this point.

A clever nomogram, involving a network of straight lines, for solving the analogous problem of the great circle distance between two points on a sphere has been devised by Friauf (Friauf, 1935, Fig. 1). A more detailed description of the method is given in Friauf, 1941, and a reproduction of the Friauf network which we have used is shown as Fig. 1.

NOMOGRAMS FOR FIXED LATITUDE

Two simple types of nomograms have been constructed. The first type is for a fixed latitude. For a fixed latitude, a curve may easily be drawn on the Friauf network and calibrated in terms of declination. Since the declination for both sun and moon is confined between 30° north and 30° south declination, it is only necessary to draw part of the curve, which may be proved to be an arc of an ellipse. This same procedure is used in the analogous problem by Friauf (Friauf, 1935, Fig. 2). The scales for λ ("included angle") and θ ("side opposite included angle") are simple cosine scales for the angles marked.

We then have a nomogram from which the value of θ can be read immediately for known δ and λ. We are not interested in θ itself but in the tidal gravity, G. We therefore recalibrate the θ scale so that it reads tidal gravity directly. The recalibration can be easily computed for we have

$$G = K(\cos^2 \theta - \tfrac{1}{3}),$$

where K is the constant which will yield gravity values in 0.01 mg. units. We set

$$K(\cos^2 \theta - \tfrac{1}{3}) = n,$$

where n is 0 or a positive or negative integer. If we solve this equation for $\cos \theta$ we have

$$\cos \theta = \sqrt{\frac{n}{K} + \frac{1}{3}}.$$

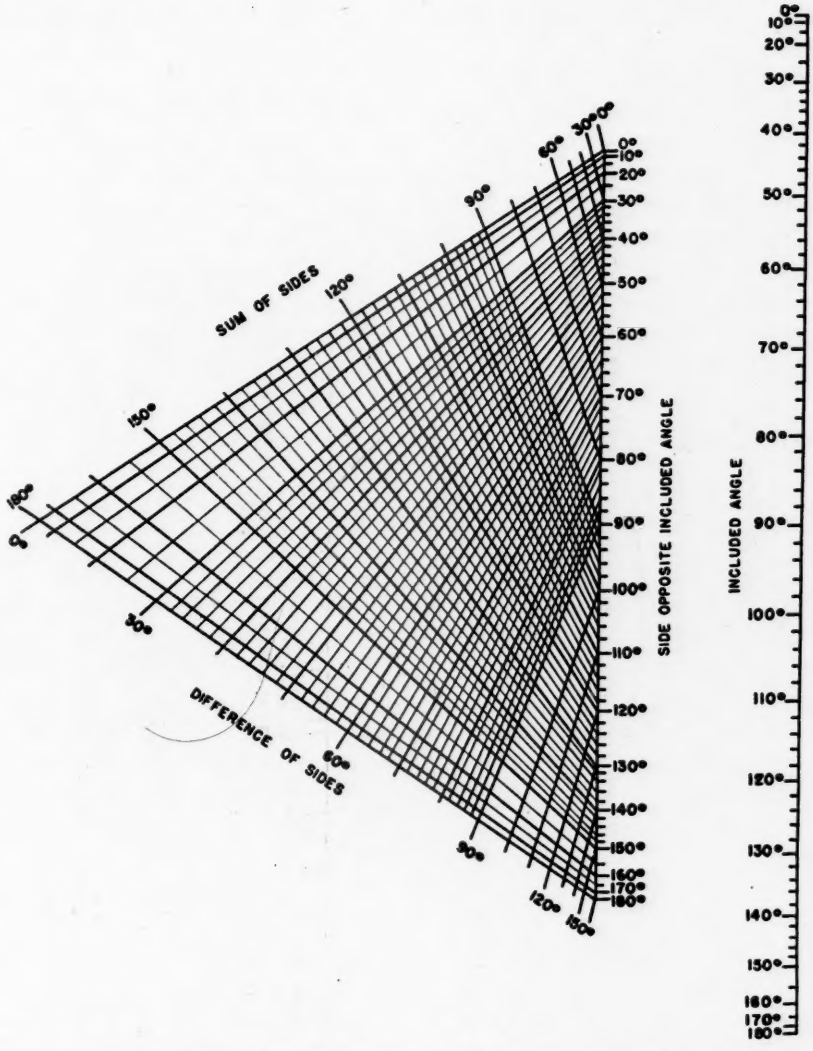

FIG. 1. Friauf nomogram for solution of spherical triangles. This is Fig. 1 of Friauf, 1941, and is reproduced here through the courtesy of Dr. James B. Friauf and the *Journal of the Franklin Institute.*

The values of this for successive values of n will give us the calibration distances we wish for a calibration in 0.01 mg units, provided we multiply by some modulus, C, to take care of the scale to which the nomogram is drawn. In the nomograms made so far this modulus has been

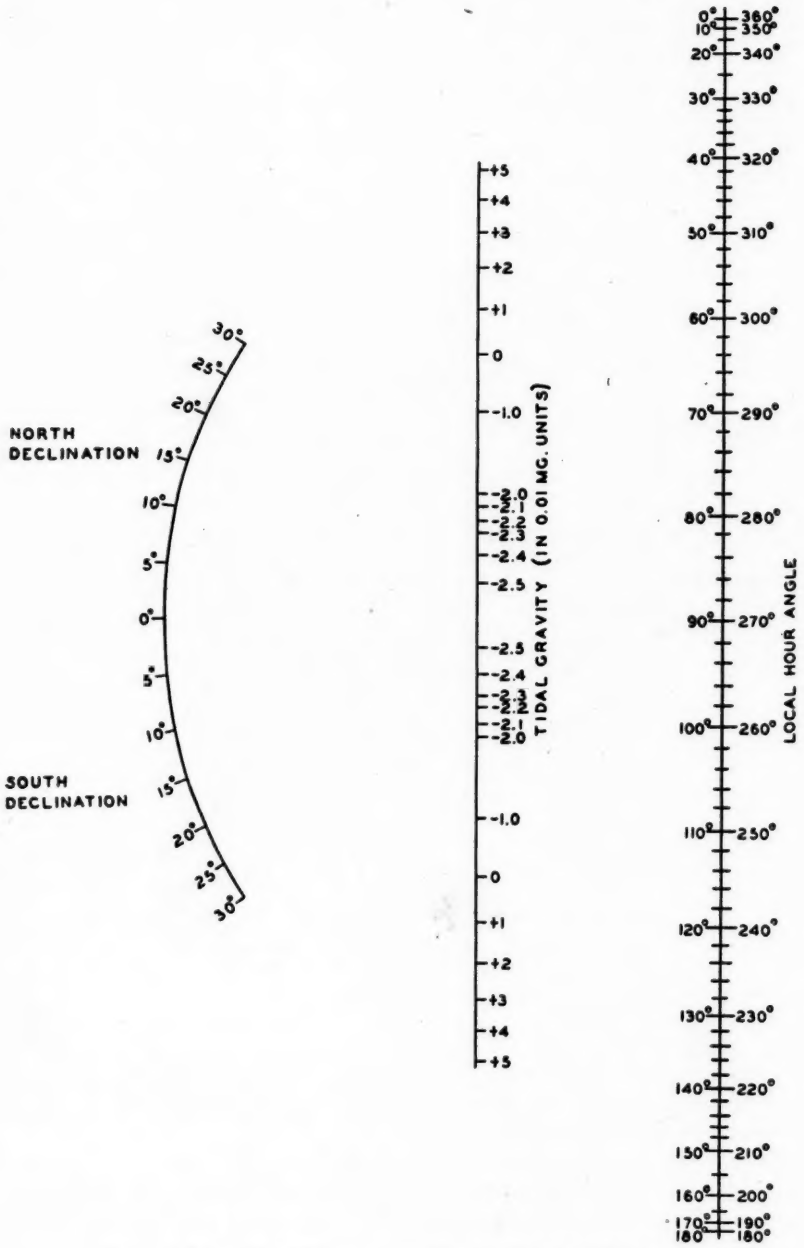

FIG. 2. Solar tidal gravity nomogram for latitude 40°32′.7 N.

11/3 inches; that is, the complete cosine scale (from 0° to 180°) is 22/3 inches long.

A solar tidal gravity nomogram made by this procedure is shown in Fig. 2 for the latitude of Harmarville, Pa., which is 40°32′.7 N. To use the nomogram to compute the tidal gravity at a particular time and position, one must know the declination and the local hour angle of the sun. The declination and the Greenwich hour angle are listed for Greenwich civil time in such publications as *The American Nautical Almanac* or *The American Air Almanac* (which is much more conveniently arranged for our purposes). The Greenwich civil time can be computed easily for any locality as soon as one knows what variety of standard or local time is being kept there. The declination can then be found from the almanac, while the local hour angle is found by subtracting the longitude of the position from the Greenwich hour angle given in the almanac. The point on the tidal gravity scale which is cut by a straight line connecting the points on the declination and local hour angle scales marked with the values just found indicates the corresponding tidal gravity value. Instead of drawing a straight line through the two given points, it is more convenient to use a transparent straight edge (such as a side of a triangle) or a straight line scratched on a piece of celluloid.

The lunar tidal gravity nomogram, shown in Fig. 3 for the latitude of Harmarville, is used in the same fashion, except that when the distance of the moon is not at its mean value (which corresponds to a horizontal parallax of 57′), it is necessary to multiply the value read from the nomogram by the factor for the horizontal parallax at that time. The horizontal parallax of the moon is listed in both of the almanacs mentioned above.

NOMOGRAMS FOR FIXED LATITUDE AND LONGITUDE

If the nomogram is to be used at a fixed position, it is possible to recalibrate the local hour angle scale in terms of Greenwich hour angle (GHA). This can be done easily. The distance from the center of the local hour angle scale is $C \cos \lambda$, where C is the modulus. If $L°$ is the longitude and $H°$ the Greenwich hour angle, we then have the distance from the center equal to $C \cos (H° - L°)$ and the new scale will be marked at that distance with the value $H°$. In the nomograms made so far the value of C has been 5 inches.

A solar tidal gravity nomogram made by this procedure is shown in Fig. 4 for Harmarville, Pa. (latitude 40°32′.7 N and longitude

DISTANCE PARALLAX	FACTOR
54′	0.85
55′	0.90
56′	0.95
57′	1.00
58′	1.05
59′	1.11
60′	1.17
61′	1.23
62′	1.29

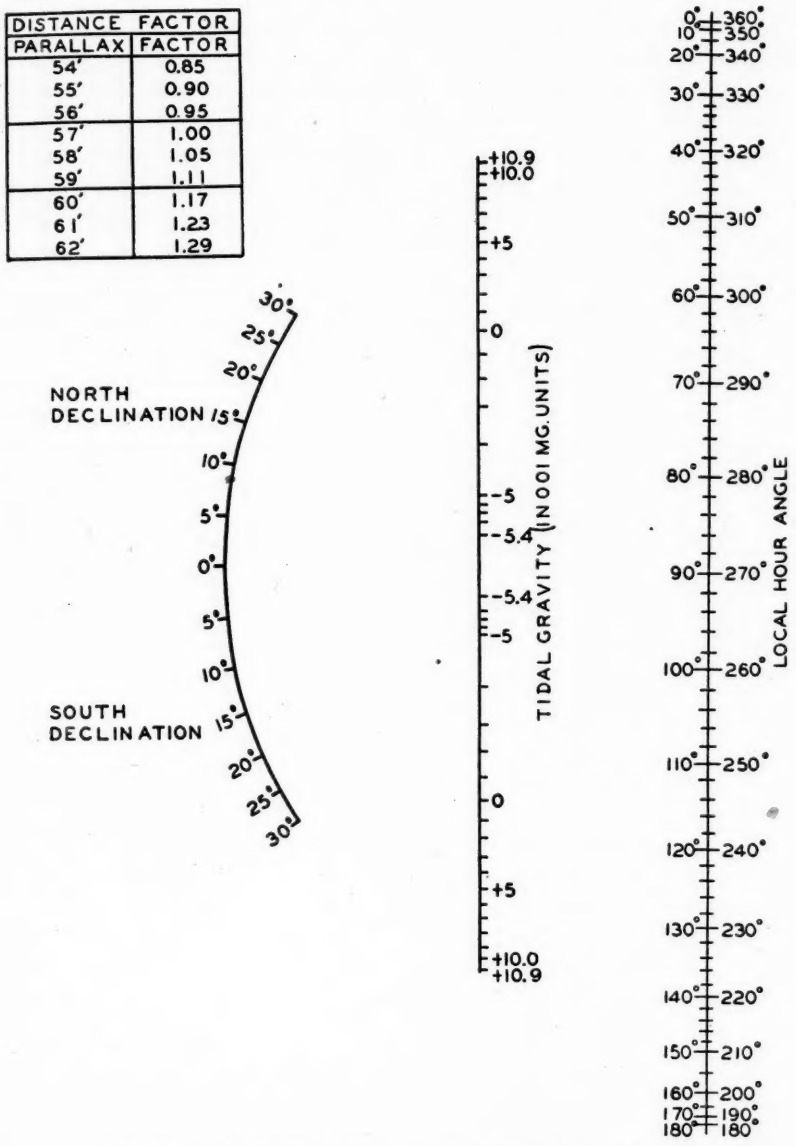

FIG. 3. Lunar tidal gravity nomogram for latitude 40°32′.7 N.

79°49′.6 W); the corresponding lunar nomogram is shown in Fig. 5. With the use of the recently started publication, *The American Air Almanac*, the astronomical data needed for both nomograms are all

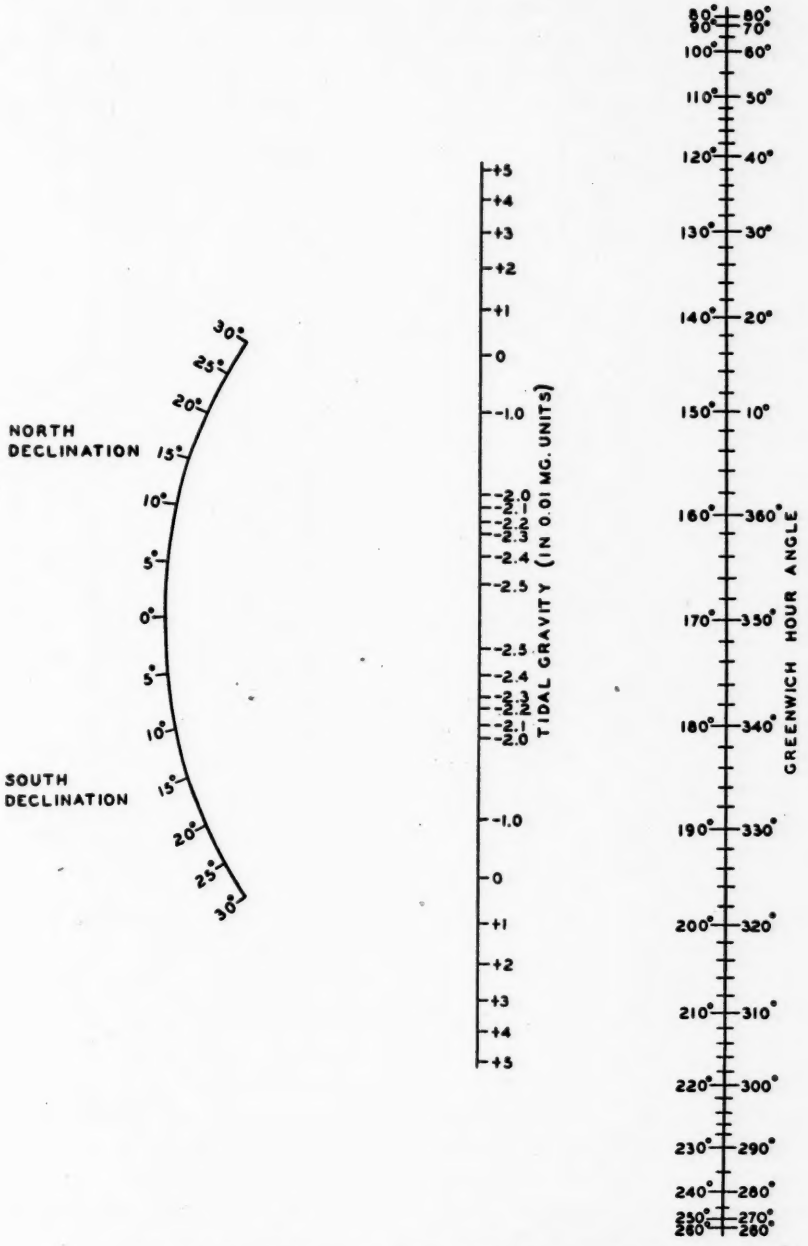

FIG. 4. Solar tidal gravity nomogram for Harmarville, Pa.

DISTANCE PARALLAX	FACTOR
54′	0.85
55′	0.90
56′	0.95
57′	1.00
58′	1.05
59′	1.11
60′	1.17
61′	1.23
62′	1.29

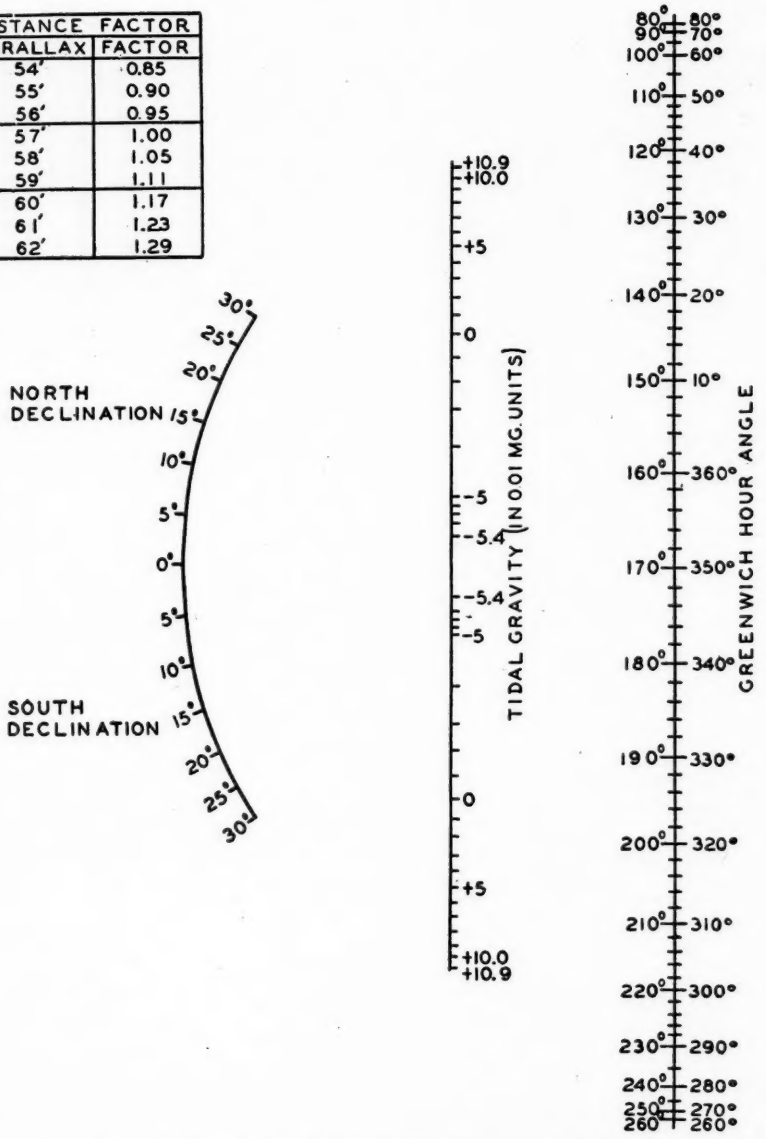

FIG. 5. Lunar tidal gravity nomogram for Harmarville, Pa.

on the same page (with one exception) and the computation is a simple routine matter of noting the Greenwich hour angle and the declination and reading the nomogram for the value of tidal gravity. Since the

data in *The American Air Almanac* are given at intervals of 10 minutes of Greenwich civil time, it is possible in computing a curve of tidal gravity to choose the time so that the printed values can be used directly and no interpolation or other computation will be necessary. The one exception mentioned above is the horizontal parallax of the moon, which is given at noon, Greenwich civil time, every other page, since two pages are used for each day. *The American Air Almanac* is thus the ideal publication for locating the data needed.

ACCURACY OF THE NOMOGRAMS

To study the accuracy of the values found from these nomograms, tidal gravity values were computed at two-hour intervals over the

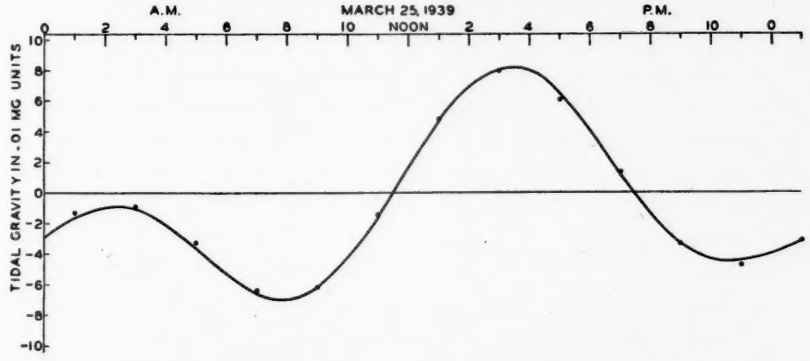

FIG. 6. Comparison of tidal gravity at Harmarville, Pa., computed by the nomogram method with that computed by U. S. Coast and Geodetic Survey tide-predicting machine No. 2. Time is Eastern Standard. The curve is based on the Coast and Geodetic Survey calculations, while the nomogram results are shown by the circles.

period of a day at Harmarville using the nomograms for fixed latitude. The errors were determined by comparison with values read from a curve computed for the laboratory by the U. S. Coast and Geodetic Survey with its tide-predicting machine No. 2. The results are shown in Fig. 6. In making the comparison 0.009 milligal was subtracted from the values read from the Coast and Geodetic Survey curve in order to take care of a quasi-constant term which was not included in the original computation.

The accuracy shown in Fig. 6 is sufficient for present purposes in connection with gravimeter work. The largest deviations shown are 0.004 milligal (one case positive, one case negative) while the average of all the deviations, without regard to sign, is about 0.002 milligal.

COMPARISON WITH ADLER'S METHOD

It is of some interest to compare the nomogram method with the chart method of Adler (Adler, 1942). It is at once obvious that the basic purposes of the two are different, for the nomogram (especially the fixed point type) is intended to yield rather accurate values at a single location, while the chart is intended to yield somewhat less accurate values at any location over a large area.

By using the original network of straight lines instead of drawing one curve for a fixed latitude value, or by drawing a network of curves for conveniently spaced values of latitude, it would be possible to extend the nomogram method to cover a large area. Such an extension, however, would be gained only by the loss of the simple routine character of the computation made with the fixed point chart.

Two differences in the underlying theory of the two methods are at once evident. The nomogram method corrects for the change in lunar distance, which is neglected in the chart method. Again the nomogram method makes no provision for correction factors which are intended to make the computed values agree more closely with those observed. Field work by the Gulf Research & Development Company has shown that such correction factors are far from constant (Lambert, 1940, page 13). Further, it is not believed that sufficient observational data are yet available to prove that such factors are constant in time. It would thus seem preferable not to incorporate such factors in either charts or nomograms, but to introduce them in a final multiplication, if their use is desired.

ACKNOWLEDGMENTS

The writer wishes to express his appreciation to Mr. W. L. Dowler, who prepared the figures and constructed the nomograms for this paper; to Dr. James B. Friauf and the *Journal of the Franklin Institute*, for permission to reproduce the diagram used as Fig. 1; and to Dr. Paul D. Foote and Dr. E. A. Eckhardt, for permission to publish this paper.

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UTILITY OF THE ELECTRIC METHODS IN GEOPHYSICAL EXPLORATION*

H. M. EVJEN†

ABSTRACT

The theoretical possibilities and the physical background of electric methods are considered in a qualitative manner. A rigorous mathematical treatment of the problem is at present a practical impossibility because the electric properties of the ground are not sufficiently well known. By analogy with the seismic method of exploration, however, where the rigorous physical optics governing the transient generated by the exploding dynamite, and the propagation of said transient in general, have been sadly neglected, this lack of mathematical rigor should not be a serious stumbling block. It is concluded that the possible utility of electric methods can be best appraised in terms of the known utility of electric well logging. This possibility, according to the author's experience, can be attained only by a departure from the traditional electric methods. One such departure is described in general terms.

The present account of electric methods in geophysical exploration will be confined mainly to a qualitative consideration of the physical background of the problem. Even though a rigorous mathematical treatment would be very gratifying, the labor involved in detailed numerical calculations is tremendous because most of the integrals cannot be evaluated in finite form. Before one delves into such work, therefore, it is important that the course be well charted so that one does not get lost in a morass of meaningless equations and numbers.

The first question to be answered naturally concerns the ultimate, fundamental value of electric exploration. That is, is it worth one's while to go to all kinds of trouble in order to find out what the electric properties of the ground are at various specified locations and depths? The answer fortunately is simple and unequivocal. Oil and most of the minerals in which interest exists, are defined through their electric properties, such as the electric resistivity, in a manner which can be said to be not easily equalled by other accessible characteristics.

The success of electric well logging confirms this conclusion. However, it must be remembered that the formations are disturbed in electric well logging. For instance, a serious source of trouble in many localities has been the leakage of salt water from one formation along the length of the bore hole and into another. If the electric properties of the formations could be probed from the surface with reasonable

* Read by title at the Denver meeting, April, 1942.

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accuracy, but without the necessity and expense of drilling a hole, the results would apply to the undisturbed formations and naturally would be much more valuable.

The question remains, can the formations be probed with reasonable accuracy from the surface of the ground? Before this question can be answered the means to be employed must be specified.

If only direct current were to be used the answer can be given without appeal to theory. Some elementary considerations show that whether we probe the resistivity of the ground by sending direct current through grounded electrodes or whether we probe the magnetic permeability of the ground by sending a direct current through a closed loop, only relatively simple potential theory is involved. The electric method in these cases is more or less reduced to the status of gravitational or magnetic methods which also are based on potential theory.

More important, however, is the fact that direct current has been tried by a great many able and skilled investigators with disappointing results. It is true that for practical reasons many of these workers did not actually use direct current but used commutated or alternating currents of frequency so low that direct current was believed to be approached. It now can be stated definitely that this belief, in a majority of cases, was not justified.

The application of the direct current theory to the interpretation of the results therefore was in error. This, however, was not the main reason for the failure of the work.

In order to understand the real reason for the failure one must forget the idealized horizontally layered, laterally homogeneous earth and remember the real earth with its topography and drainage patterns, not only at the surface, but frequently immediately below an innocently flat terrain. In other words, it must be remembered that the shallow layers in the ground are apt to change their electric properties violently in horizontal directions.

Any method which utilizes, as a working hypothesis, a horizontally layered ground must recognize the effect of departure from homegeneity in horizontal directions, particularly in the shallow layers. Otherwise it is doomed to failure.

Needless to say, numerous attempts have been made to eliminate the effect of horizontal changes in shallow layers. This usually has been done by various averaging processes meant to neutralize the effect of changes in shallow layers. The problem involved is not theo-

retically impossible but, for practical purposes, it probably can be said to be well nigh hopeless in many areas.[1]

In analyzing the difficult problem here involved one finds that the moving of the grounded electrodes from one location to another during a "run" is the main source of trouble. One naturally would not mind large shallow effects if these would only remain constant over the distance involved in a "run" so that the interpretation of the results in terms of deeper horizons would not be affected. If, on the other hand, the changes in the shallow effects, produced by moving the electrodes, are greater than the deep effect for which one is looking, the problem assumes a more serious aspect.

The problem is similar to that of the so-called weathered layer in seismic work. It is much worse, however, because there is no simple and obvious correction.

By thus drawing a parallel with the seismic problem many interesting and valuable conclusions can be reached. The methods used in conventional electric prospecting were strangely reminiscent of refraction shooting in seismic work. By the conventional "expansions" in direct current work the resolution or separation of deeper from shallower horizons was brought about in virtue of the fact that deep layers have a relatively greater effect upon the measurements for larger than for smaller electrode separations. Similarly in refraction shooting deep layers were resolved from shallow ones by the time-distance relationship.

It will be recalled that the greatest step forward in seismic work came with the advent of reflection shooting. Hence it is appropriate to examine the possibility of a similar development in the electric field. It is possible that such an idea led to the transient method of electric exploration,[2] which in fact, has many elements in common with reflection shooting.

The transient method, like the direct current methods, has been tried by able and skillful investigators. The available results, however, have not measured up to reasonable expectations.

From the school of theoretical geophysicists this apparent lack of success has been explained in terms of the theoretical lack of resolving power of the method. Such a lack of resolving power is to be

[1] However, see West and Beacham, *U. S. Patent #2,217,780*, and Beacham, *U. S. Patent #2,231,048*. (ED.)

[2] See L. W. Blau, *U. S. Patent #1,911,137*.

expected on the basis of an approximation theory in which displacement currents are totally neglected. In view of some experimental evidence, to which reference presently will be made, the validity of the assumptions underlying this theory is doubtful.

However, even granting that the resolving power of the transient method does not compare with that of reflection shooting, it must be remembered that the only reason why geologic structure has been the main-stay of geophysical exploration is that structure has been more amenable to exploration and that accumulation of minerals frequently is associated with certain structural conditions. Granted that reflection shooting, with some notable exceptions, affords the most accurate available method of mapping structure, such structure is not the ultimate objective of geophysical exploration. It will be remembered, for instance, that stratigraphic traps for oil do exist, and that structures which, according to the seismographs have good closures, do not always produce oil.

In other words, even though the transient method of exploration may be theoretically inferior to reflection shoting in the mapping of most structure, it has the decided theoretical advantage that it is working on the electric rather than on the elastic properties of the medium. Therefore, it is fundamentally better adapted for the direct detection of such minerals as oil without regard to structure.

It may be asked then, is it because too much emphasis has been placed on structure that the transient method has not been a success according to available results?

The answer, or at least one answer, can be given without appeal to elaborate mathematics.

A few elementary considerations will show that great precision is required in the transient measurements. The direct current effect of deep horizons, which can be easily computed, gives the order of magnitude of the potentials which must be observed and measured accurately. Although these potentials turn out to be easily measurable by themselves, they are superposed on a background of electric ground disturbance which ordinarily makes sufficient precision unattainable. Also, much misconception apparently has existed concerning the speed of travel of electromagnetic waves in a conducting medium such as the ground. The transient has been measured at time intervals of the order of a few hundreths of a second. In order to apply to a reasonable depth of several thousand feet, the transient should be measured at a time interval of the order of one second. The elementary

theory to prove this has been previously presented.[3] Such long time intervals, of course, make the accurate measurement of the transient even more difficult.

It is not here contended that means do not exist for making transient measurements sufficiently precise. Such means may very well already have been found although the writer is not aware of them. If such means could be developed the transient method undoubtedly would assume new importance.

Another avenue of approach exists, however, by which the necessary precision is more easily attained. This, as will be presently seen, involves the same theoretical possibilities as the transient method, but minimizes the problem of background noise by the expedient of averaging it out; that is, by the use of alternating currents.

Paradoxically, alternating currents have been extensively used in so-called direct current work for the very purpose of averaging out interference, but the idea of using alternating current for its own sake appears to have been relegated to the background. It was early recognized that the penetration of alternating current into the ground rapidly decreases for increasing frequency. Hence, it was possibly concluded, direct current should be used in order to insure maximum penetration. Besides, the theory of alternating currents in the ground was much more complex than the relatively simple potential theory of direct current. As a matter of fact, the moment alternating currents are used one is faced with the phenomenon of electromagnetic waves. Moreover, the wave lengths are surprisingly short and the speed of travel is surprisingly low in a medium of high conductivity, such as the ground.[4] The problem, therefore, is definitely one of physical optics, and it is well known that the problems in this category easily can assume such proportions as to tax the very best mathematical brain, particularly when it comes to the evaluation of multiple integrals which cannot be presented in finite form.

This does not imply, of course, that the problem presents insurmountable difficulties. Formally, in fact, the solutions can be presented with relative ease. The real difficulties begin when numerical results are required in any specific case. The labor involved in the numerical calculations frequently is tremendous.

Therefore, it is not surprising that the theory of alternating cur-

[3] H. M. Evjen, Geologie & Mijnbouw, *1*, 1, p. 2, January, 1939.
[4] H. M. Evjen, *loc. cit.*

rents in the ground has been somewhat neglected. Other reasons for this state of affairs can be given. In the first place, there has been a lack of motive for extended and laborious calculations because no simple and practical evidence has been offered indicating any possible great value of such work.

Useful field results have been practically non-existent and a fairly simple and lucid philosphical foundation has not previously been offered. In the second place, although this has not been generally recognized, the electric properties of the ground have not been sufficiently well known to warrant extended calculations. For instance, the dielectric constant of the ground may, under certain conditions similar to those existing in electrolytic condensers, become very great so that this quantity cannot be neglected even at very low frequencies.[5]

To some extent these same causes have also been at work in retarding the experimental development. Other reasons, too, have contributed their share. The technical difficulties are considerable when low frequencies are used, especially when the natural attempt is made to use sinuosidal currents. When it is realized that commutated currents serve exactly the same purpose, the problem is much simplified, but difficulties still remain.

In regard to the square wave-shapes of commutated currents, there has been a definite tendency to consider these in the light of Fourier analysis and to expect the prominent third, fifth, and other odd harmonics to stand out in bold relief and perhaps give rise to "ghosts." As a matter of fact, if the square waves are treated by Fourier analysis, very slowly converging series are obtained, making progress very painful to say the least. The square waves, however, can be built up from the well known "step-functions," in the very same manner in which a steady state is built up when the commutated current is first turned on. Rapidly converging series are then obtained, and it is found that the results do not differ radically from those obtained by considering only the fundamental frequency in the Fourier analysis. This, however, is not the place for a detailed consideration of this interesting mathematical problem.

It probably can be said that a frequency range from less than one

[5] Field results and laboratory tests, not yet published, indicate that values of the dielectric constant as high as 10^{11} may sometimes occur. With such values our concepts would have to be radically changed.

cycle per second up to ten formed a totally unexplored region where no previous technique was available. The old means of commutation used in so-called direct current work were soon found to be inadequate. The frequency of commutation and all phase-relations involved must be very accurately controlled in order to insure sufficient precision in the measurements.

The meticulous research here implied naturally could not be carried out without substantial guide posts. Some insight into the philosophical background may perhaps be gained by recalling again the transient method of exploration.

More intuitive feeling is associated with the latter than with any steady state method, probably because it is, superficially at least, so similar to reflection shooting. It was concluded in the previous pages that one of the chief drawbacks of the transient method was the difficulty of getting sufficient precision due to background noise. It is well known that if the results of observation were known at all frequencies (each frequency, of course, constituting a steady state which is observed as such), then Fourier analysis will yield the results which would have been obtained by the observation of any kind of transient. Therefore, the observation of a spectrum can be said to be equivalent to the observation of a transient. Hence, by observing a reasonably complete spectrum one has at least accomplished as much as can be accomplished by accurate transient measurements. The computation of the transient, however, would be a tedious process and hardly would be worth one's while except for academic purposes. The spectrum itself yields directly the more significant facts and by far exceeds the present capability of the transient in regard to accuracy. In order to understand how these facts can be directly obtained from the spectrum, a slightly different point of view is helpful. It will be assumed, therefore, that the measurements are started with direct current and from this state, or zero frequency, the frequency of the exploring current is increased in small steps, a potential measurement being made at each step. As the frequency is increased the penetration of the current into the ground changes because the impedance of the whole circuit at each frequency is a minimum and this requires a re-orientation of the current lines when the frequency is changed.

In general, the penetration of the current tends to become smaller as the frequency is increased. This decrease in penetration affects the deeper current paths first. Naturally, if no appreciable current penetrates to a certain depth, then the interfaces or layers at this depth no longer can have an appreciable effect on the measurements. But we

know exactly what effect these layers had at zero frequency because we can compute direct current cases with relative ease. In other words, a known effect is wiped out for a sufficient increase in frequency. If the computed effect is sufficiently large then we should be able to measure it. By the magnitude of the effect conclusions can be drawn concerning the electric contrast of the layer being wiped out. If the layer contains salt water, it is one thing; if it contains an appreciable amount of gas and oil, it is quite another. Thus the electric properties can be probed. The depth is obviously determined by the frequency at which the effect is wiped out because deeper images are wiped out first when the frequency is increased from zero. Naturally we would like to know the pattern according to which the effect is wiped out; but this requires detailed theory, and before one delves into numerical evaluation of multiple integrals requiring an enormous amount of labor and much valuable time, one naturally would like to make reasonable assumptions concerning the electric properties of the ground. If the assumptions are wrong, then the results obviously cannot be right, and may, in fact, do more harm than good because they are misleading.

Calculations have been carried out for a conventional, uniform, Ohmic ground of negligible dielectric constant, having only one reflecting interface. The results show clearly the wiping out of the effect of the interface and the frequency at which it occurs. The latter is such that the wave length of the associated electromagnetic wave is approximately four times the depth to the reflecting interface when the in-phase component of the potential is observed. This is to be expected quite in general. The pattern according to which the effect is wiped out by this theory, however, probably comes out much too broad because the dielectric constant and its anomalous behavior have been completely ignored. At any rate, a large variety of field data, in which the best possible subsurface control was had, indicate that the quarter wavelength criterion is fulfilled whereas the pattern according to which the effect is wiped out is much sharper than predicted by the elementary approximation theory. In other words, the resolving power of the method is greater than predicted by the imperfect theory.

Since most of the evidence to support this statement has been accumulated in the course of commercial operations, it is obviously impossible to present it all. In a different place,[6] the results of some

[6] H. M. Evjen. *Electric Exploration for Oil.* Austin Meeting of the A.I.M.E., October, 1942.

field experiments from West Texas have been presented in detail. These rather crucial experiments show clearly that shallow layers have no effect upon the observed quantities used in the interpretation, and secondly, they show that effects, which hardly can be anything but deep, are wiped out abruptly for increasing frequencies. In other places, where electric well logs have been available, the frequencies at which the extinctions occurred have been correlated positively with the depths to the electric markers appearing in the electric well logs, according to the quarter wave length criterion. Thousands of stations have been measured and although some failures naturally have occurred the statistical evidence overwhelmingly favors the conclusions here drawn.

Due to the quarter wavelength criterion it is possible by this method to map structure. It will be noticed that the electrodes are not moved during a "run"; only frequencies are varied. Shallow effects therefore remain constant during a "run" and are positively eliminated from the interpretation. The shallow layers ordinarily have a relatively high resistivity which makes the velocity of propagation of the electromagnetic waves in them relatively high. The so-called weathering corrections which are so important in seismic work therefore ordinarily can be neglected in this work. In fact, the structure obtained is substantially mapped with reference to a more or less level water table, so that not even elevation corrections ordinarily need to be applied.

Although it is thus seen that this method of mapping structure has many advantages, experience with it has indicated that structural mapping obviously should not be considered as its primary function. The seismograph has greater resolving power, and, perhaps in a majority of cases, it is more accurate. Exceptions, however, do exist. One such exception is afforded by areas where unsuitable surface conditions, such as the presence of glacial drift or of relatively shallow high velocity beds, interfere severely with seismic work without equally impeding an electric survey. Another is afforded by the increasingly important fault mapping, where systematic variations in the seismic velocity, caused for instance, by lowered speed of the elastic waves in the broken up fault zone, may tend to wipe out the seismic throw so that the reflection shooting fails to detect even sizeable faults.[7] The electric method hardly ever fails to detect a fault,

[7] See, for instance, B. G. Swan, GEOPHYSICS, VII, p. 367 (October, 1942).

but may also detect some that are definitely secondary and might perhaps better be forgotten. The faults are detected electrically by several different criteria. Only rarely is the fault detected by the sudden change in elevation of a key horizon. Occasionally the contraction of intervals associated with normal faults can be directly observed. Invariably, however, the fault zone itself has a marked electric contrast, giving rise to characteristic electric anomalies which can be traced horizontally. Depending on the depth from which maximum effect is obtained, and the hade of the fault, different traces will be obtained. Faults, amounting to little more than fissures, may have a considerable electric contrast and, hence, may give strong manifestations of the latter kind.

Even though erroneous and incomplete fault pictures have undoubtedly accounted for a large number of dry holes on apparently high closure, exaggerated emphasis must not be placed on the ability of the electric method to map faults. The mapping of strucure by the electric method involves a slower field procedure because measurements must be made at a very large number of frequencies. The interpretation of the results also is more difficult. On the other hand, it is a relatively simple matter to obtain a measure of the electric contrast or the "reflecting power" of interfaces at a certain range of depths. This involves a much reduced number of measurements and almost invariably indicates the local presence of oil, gas, or other insulating material.

Where the structure is very complicated, due to faulting, or where the accumulation of oil is definitely stratigraphic, one is forced to remember that the purpose of geophysical exploration is to find oil and other minerals and not structure. Due to the success of structural exploration in recent years this fact sometimes is forgotten. In the electric work, done to date, it has been more or less necessary to place structure first. The direct evidence for oil has been cautiously introduced as something secondary. By those actively engaged in the field it is more and more realized that this procedure amounts to putting the cart before the horse. Structure undoubtedly is important in this work too, but it probably should take second place.

All-in-all the results obtained from this new type of electric exploration bear considerable similarity to those obtained from electric well logging. Nowhere near the same detail is obtained, of course, but, to compensate for this lack of detail, an horizon may be traced and followed in horizontal directions.

It is well known from electric well logging work that high absolute values of the resistivity of a certain sand do not necessarily mean oil saturation. On the other hand, if one and the same sand can be traced and followed horizontally and the resistivity of this sand changes locally from relatively low to relatively high values, the presence of some insulating material is better established. This possibility illustrates well the potential value of electric exploration.

THE MUTUAL IMPEDANCE OF COLLINEAR GROUNDED WIRES*

S. S. WEST†

ABSTRACT

The formula of R. M. Foster for the mutual impedance of grounded wires lying on the surface of the earth has been evaluated for the case where the wires are grounded at points which are collinear and equally spaced upon the surface of a homogeneous earth. Curves are given showing mutual impedance and phase shift as functions of resistivity and frequency.

In the study of electrical methods of prospecting, one frequently wishes to determine the relation between a current flowing between two electrodes in the surface of the earth and the resultant electromotive force produced in a circuit connecting another, similar pair of electrodes. This problem is identical with the determination of the mutual impedance of the wires joining electrodes of the pairs. It was first attacked by A. E. Bowen and C. L. Gilkeson,[1] who made extensive measurements of the mutual impedance of parallel grounded circuits to determine the magnitude of inductive coupling between power and telephone lines. They interpreted their results in terms of a horizontally-stratified earth of two layers, assuming one of the circuits to be an infinitely long straight line. Later, R. M. Foster[2] published a formula for the mutual impedance of grounded wires of finite length lying on the surface of a homogeneous earth, and John Riordan and E. D. Sunde[3] published a more general formula for the mutual impedance of grounded wires lying on the surface of a two-layer earth.

It is not difficult to obtain by the method of Riordan and Sunde a formal solution for three layers, but no useful result is thereby attained, for even the two-layer case is extremely difficult to reduce to numerical terms. However, one can evaluate Foster's formula for a chosen arrangement of electrodes upon the surface of a homogeneous earth and obtain a numerical relation of mutual impedance in terms

* Manuscript received December 1, 1942.

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[1] A. E. Bowen and C. L. Gilkeson. *Bell System Technical Journal*, *9*, 628 (1930).

[2] R. M. Foster. *Bell System Technical Journal*, *10*, 408 (1931).

[3] John Riordan and E. D. Sunde. *Bell System Technical Journal*, *12*, 162 (1933).

of frequency and resistivity, which will greatly assist the understanding of many methods of electrical prospecting.

Let us implant four electrodes collinearly in the surface of a homogeneous earth with a distance a between each two adjacent electrodes. Number the electrodes consecutively from one end of the line to the other. Electrodes 1 and 2 are connected together to form one circuit and electrodes 3 and 4 to form the other. The mutual impedance Z between the circuits is given by Foster[2] in the form

$$Z = \frac{1}{2\pi\lambda}\int\int \left\{\frac{d^2}{dSds}\left(\frac{1}{r}\right) + \frac{\cos\epsilon}{r^3}\left[1 - (1+\gamma r)e^{-\gamma r}\right]\right\} dSds \quad (1)$$

where the integrations are along the two wires. ϵ is the angle between the wires, so that here $\cos\epsilon = 1$. $\gamma = (4\pi i\lambda\omega)^{1/2}$, where λ = specific conductivity and ω = angular frequency. The permeability is taken as unity and the dielectric constant assumed negligible. If we take the origin at electrode 1, then one integration is from 0 to a and the other from $2a$ to $3a$. $r = S - s$, where s is the distance to a point on the near wire and S the distance to a point on the far wire.

The integrand of Z can be simplified in several ways. Since the electrode arrangement has been specified, we can carry out the differentiation in the first half of the integrand to obtain.

$$\frac{d^2}{dSds}\left(\frac{1}{r}\right) = \frac{d^2}{dSds}\left(\frac{1}{S-s}\right) = -\frac{2}{(S-s)^3} = -\frac{2}{r^3}. \quad (2)$$

The second half of the integrand is a complex quantity because it contains γ, and we must separate it into its real and imaginary parts. Accordingly,

$$\gamma = (4\pi i\lambda\omega)^{1/2} = (4\pi\lambda\omega)^{1/2}\cdot\left(\frac{1+i}{\sqrt{2}}\right), \quad (3)$$

since

$$\sqrt{i} = e^{\pi i/4} = \cos\frac{\pi}{4} + i\sin\frac{\pi}{4} = \frac{1+i}{\sqrt{2}}. \quad (4)$$

If we let ρ = specific resistivity and f = frequency, $\lambda = 1/\rho$ and $\omega = 2\pi f$, so that

$$\gamma = \left(8\pi^2\frac{f}{\rho}\right)^{1/2}\cdot\left(\frac{1+i}{\sqrt{2}}\right) = 2\pi\left(\frac{f}{\rho}\right)^{1/2}\cdot(1+i) = \beta(1+i). \quad (5)$$

We have thus defined

$$\beta = 2\pi\left(\frac{f}{\rho}\right)^{1/2} \tag{6}$$

which is a real quantity.

The complex part of the integrand is reduced as follows:

$$\begin{aligned}(1+\gamma r)e^{-\gamma r} &= (1+\beta r+i\beta r)(\cos\beta r - i\sin\beta r)e^{-\beta r}\\ &= e^{-X}(1+X+iX)(\cos X - i\sin X), \text{ where } X=\beta r.\\ &= e^{-X}[(1+X)\cos X + X\sin X]\\ &\quad + ie^{-X}[X\cos X - (1+X)\sin X].\end{aligned} \tag{7}$$

We have from Foster's formula (with $\cos\epsilon = 1$)

$$Z = \frac{1}{2\pi\lambda}\int_0^a\int_{3a}^{2a}\left\{\frac{d^2}{dSds}\left(\frac{1}{r}\right)+\frac{1}{r^3}\left[1-(1+\gamma r)e^{-\gamma r}\right]\right\}dSds. \tag{8}$$

Substituting our result for $(d^2/dSds)(1/r)$ and integrating, we obtain

$$\begin{aligned}2\pi a\lambda Z &= \tfrac{1}{3} + i2\pi\lambda\omega a\int_0^a\int_{3a}^{2a}\frac{dSds}{r}\left\{\frac{2}{(\gamma r)^2}\left[1-(1+\gamma r)e^{-\gamma r}\right]\right\}\\ &= \tfrac{1}{3} + i\beta a\int_0^a\int_{3a}^{2a}\frac{2\beta^2 dSds}{\beta r(\gamma r)^2}\cdot\left[1-(1+\gamma r)e^{-\gamma r}\right]\\ &= \tfrac{1}{3} + \beta a\int_0^{\beta a}\int_{3\beta a}^{2\beta a}G(\beta r)dS'ds',\end{aligned} \tag{9}$$

where $S'=\beta S$, $s'=\beta s$, and

$$\begin{aligned}G(\beta r) &= \frac{2i}{(\gamma r)^2\beta r}\left[1-(1+\gamma r)e^{-\gamma r}\right]\\ &= \frac{1}{(\beta r)^3}\left[1-(1+\gamma r)e^{-\gamma r}\right]\\ &= -\frac{1}{X^3}\left[e^{-X}\{(1+X)\cos X + X\sin X\}\right.\\ &\quad \left. + ie^{-X}\{X\cos X - (1+X)\sin X\} - 1\right]\end{aligned} \tag{10}$$

Here $X=\beta r$ as before.

Let the real part of $G(X)$ be represented by $G_1(X)$ and the imaginary part by $G_2(X)$. Then

$$G_1(X) = \frac{1}{X^3}\left\{1 - e^{-X}[(1 + X)\cos X + X \sin X]\right\} \tag{11}$$

$$G_2(X) = \frac{e^{-X}}{X^3}[(1 + X)\sin X - X \cos X]. \tag{12}$$

Unfortunately, these functions cannot be directly integrated, and, to simplify the numerical integration, it is necessary to transform the integral in Z so that the double integration is reduced to a single integration. Considering the integration of any function $F(r)$ in the coordinate system we have set up, one obtains

$$\begin{aligned}\int_0^a \int_{3a}^{2a} F(r)dSds &= \int_0^a ds \int_{3a-s}^{2a-s} F(r)dr, \quad \text{since} \quad S = r + s \\ &= \int_a^{2a} F(r)dr \int_a^{2a-r} ds + \int_{2a}^{3a} F(r)dr \int_{3a-r}^{0} ds \\ &= -\int_a^{2a} F(r)(r - a)dr - \int_{2a}^{3a} F(r)(3a - r)dr \\ &= -\int_0^a F(X + a)XdX + \int_a^0 F(3a - X)XdX\end{aligned} \tag{13}$$

by putting $X = r - a$ in the first integral and $X = 3a - r$ in the second. Finally, then,

$$\int_0^a \int_{3a}^{2a} F(r)dSds = -\int_0^a [F(X + a) + F(3a - X)]XdX. \tag{14}$$

This formula can be applied to Eqs. 9 and 10 as follows:

$$2\pi a\lambda Z = \tfrac{1}{3} + R + iI$$

or

$$2\pi a\lambda \left| Z \right| = [(\tfrac{1}{3} + R)^2 + I^2]^{1/2} \tag{15}$$

where

$$R = -X_0 \int_0^{X_0} [G_1(X + X_0) + G_1(3X_0 - X)]XdX \tag{16}$$

and

$$I = -X_0 \int_0^{X_0} [G_2(X + X_0) + G_2(3X_0 - X)]XdX \tag{17}$$

in which $X_0=\beta a=2\pi a(f/\rho)^{1/2}$.

The phase angle ϕ is given by $\phi=-\tan^{-1}I/(\frac{1}{3}+R)$, a lag being taken as positive.

Since R and I are not integrable in terms of simple functions, integrals (16) and (17) were evaluated graphically, and $|Z|$ and ϕ were calculated from them. Fig. 1 is a graph of $|Z|/\rho$ as a function of f/ρ, where $|Z|$ is expressed in ohms, resistivity ρ in ohm-centimeters,

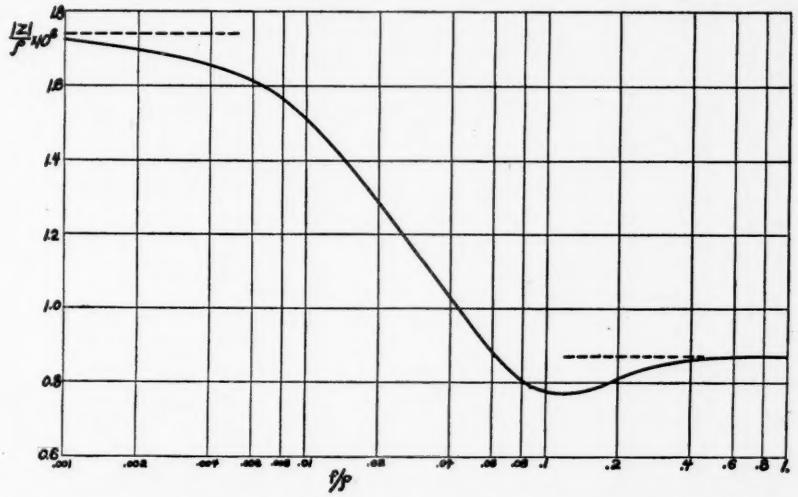

FIG. 1. Mutual impedance/resistivity as a function of frequency/resistivity for a homogeneous earth. Electrodes are collinear on the surface of the earth, with a spacing of 1000 ft. between adjacent electrodes. The source of alternating current is connected to the first and second electrodes and voltage is measured between the third and fourth. Mutual impedance is expressed in ohms and resistivity in ohm-centimeters.

and frequency f in sec^{-1}. Fig. 2 is a graph of ϕ as a function of f/ρ, with ρ in ohm-centimeters, f in sec^{-1}, and ϕ in degrees. The electrode spacing a was chosen to be 1000 feet, since this is a value frequently used in resistivity prospecting. To permit the calculation of $|Z|$ and ϕ for any electrode spacing, the values of $(6\pi a/\rho)|Z|$ and ϕ are given in Table I for each value of βa.

It is interesting to note that $|Z|/\rho$ approaches horizontal asymptotes (shown in Fig. 1 by dotted lines) as f/ρ becomes very large or very small, and that the asymptotic values of $|Z|/\rho$ differ by a factor of 2. This can easily be verified from the original formula for Z by making γ zero or infinite. Other interesting features of the curves

are the minimum of $|Z|/\rho$ at $f/\rho=0.12$ and the leading phase angle near $f/\rho=0.7$.

To illustrate the sort of qualitative conclusions which one can draw from these curves, we may consider the "Eltran" method of electrical prospecting, in which it has been customary to use the electrode configuration and electrode spacing for which the curves have been calculated. From Fig. 1 one can see how the attenuation of higher frequen-

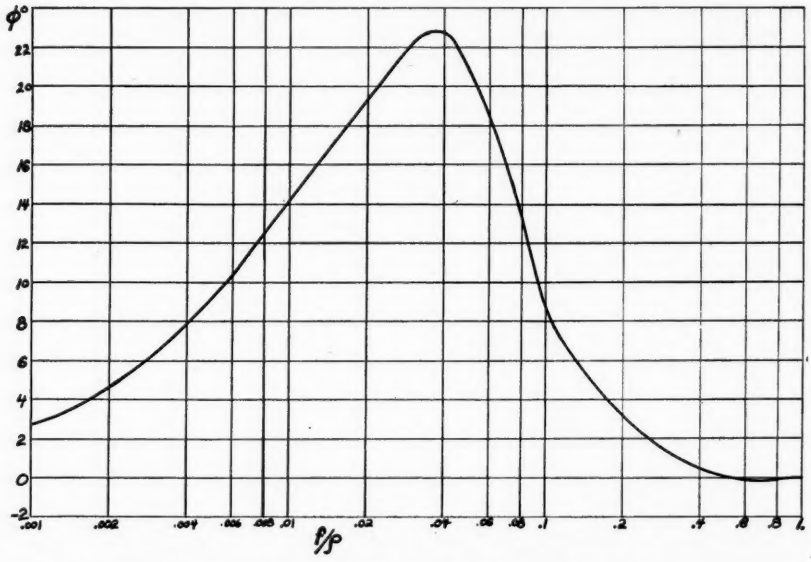

FIG. 2. Phase lag as a function of frequency/resistivity for a homogeneous earth. Electrodes are collinear on the surface of the earth with a spacing of 1000 ft. between adjacent electrodes. The source of alternating current is connected to the first and second electrodes and voltage is measured between the third and fourth. Phase is expressed in degrees and resistivity in ohm-centimeters.

cies corresponding to the right-hand portion of the curve can produce transients of large time constant by leaving the lower frequencies which correspond to the left-hand portion of the curve. As the resistivity increases, the region of attenuation moves toward higher frequencies and the time constant decreases. It should be noted, however, that small time constants (steep transients) should be expected for very small values of resistivity when a capacitance-coupled amplifier is used in the measuring system, since the mutual impedance will be the same for all frequencies large enough to be of importance, and the phase shift will be nearly zero.

TABLE I

FOR USE IN THE CALCULATION OF $|Z|$ AND ϕ FOR ANY ELECTRODE SPACING

$2\pi a\left(10^{-9}\frac{f}{\rho}\right)^{1/2}$	$\frac{6\pi a}{\rho}\lvert Z\rvert \cdot 10^{6}$	ϕ
0.02	1.000	0.04°
0.03	1.000	0.8
0.05	1.000	0.21
0.07	0.999	0.40
0.10	0.998	0.8
0.15	0.995	1.6
0.20	0.989	2.7
0.30	0.971	5.3
0.40	0.944	8.2
0.50	0.919	11.0
0.60	0.868	14.1
0.70	0.818	16.3
0.85	0.739	19.2
1.00	0.674	21.5
1.13	0.629	22.8
1.25	0.583	22.5
1.37	0.540	21.2
1.50	0.497	18.6
1.75	0.458	12.3
2.00	0.444	7.6
2.50	0.456	3.9
3.00	0.480	2.1
4.00	0.497	0.45
5.00	0.500	−0.17
7.00	0.500	0.02
10.00	0.500	0

a is in centimeters, ρ in ohm-centimeters, $|Z|$ in ohms, f in seconds^{-1}, and ϕ in degrees.

The fact that mutual impedance changes by only slightly more than a factor of 2 over the whole range of resistivity of a homogeneous earth suggests that there may be some utility in the idea of changing the effective penetration of the current into the earth by changing the frequency. Most workers in the field of resistivity prospecting have considered the substitution of variable-frequency AC with a fixed

electrode configuration for DC with a configuration of fixed proportions but variable electrode spacing, and have rejected it because of the lack of means for interpreting the data in terms of resistivities and depths to interfaces in a many-layered earth. However, since mutual impedance changes so little with resistivity or with frequency, while penetration of current changes a great deal, it might be possible to set up an approximate relation between electrode spacing in the DC case and f and Z in the AC case. For this purpose one might usefully define an "AC apparent resistivity" as the resistivity of a homogeneous earth which would yield the observed value of $|Z|$ for a given f. Still better would be the evaluation of the two-layer formula of Riordan and Sunde or an extension of it to the three-layer case, but these are imposing tasks and are not likely to be completed soon.

I wish to express my appreciation to the officers of the Stanolind Oil and Gas Company and Western Geophysical Company for permission to publish this paper.

SOME EFFECTS OF GEOLOGIC STRUCTURE ON RADIO RECEPTION*

B. F. HOWELL, JR.†

ABSTRACT

Radio fields at standard broadcast frequencies were examined over faults to determine how the geologic conditions affected the fields. The fields in rugged and densely inhabited areas were found to be too irregular to yield understandable patterns. Very small variations in the directions of the fields were suggested but not proven over the San Jacinto fault. No variations in intensity were found over the San Andreas fault, but variations were observed at some places over the Piedmont fault in New Jersey. Such variations might be due to higher conductivity of the fault zone, or to the addition of waves reflected and refracted at the fault surface. Weak areas near San Bernardino were noted, but could not be correlated with faults. It seems improbable that surveys using standard broadcast signals will be of much value in studying radio weak spots, although other approaches may be more revealing.

INTRODUCTION

The existence of shadow zones where radio reception is poor or impossible behind hills or buildings, in deep road cuts, under railway overpasses, and in tunnels or similar places is common knowledge. Less well known are the effects of overhead wires, with which are associated "weak areas," or "dead spots" as they are sometimes called, where the signals are received with less intensity than in surrounding areas. Besides these obvious cases of shielding, there appear to be other less well understood causes of weak spots of radio reception. It has been suggested that certain geologic structures, notably contacts between rocks of different composition, especially fault contacts, might have some influence on the radio-frequency fields in their neighborhood.[1] Relatively little work has been done on this problem; and what has been done has not, in most cases, been published. The result is that no clear explanation of the relationship between geologic structures and radio weak spots has been made known.

The problem undertaken was to examine certain geologic structures to ascertain if there were any irregularities in the radio field near

* Manuscript received November 1, 1942. This paper is a condensation of a report presented in partial fulfillment of the requirements for the Master of Science degree at the California Institute of Technology.

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[1] Cloos, Ernst. *Auto radio an aid in geologic mapping.* Am. Jour. Sci., series V, Vol. 28, 1934, pp. 255–268.

these structures and not the result of non-geologic influences; and to examine any known, available weak spots which appeared to be connected with geologic structure, in order to determine, if possible, exactly what the effect of the structure was.

The value of a survey of this sort arises from the possibility of developing a simple, inexpensive, new method of locating and tracing faults and contacts, especially where their position is obscured at the surface.

THEORETICAL BACKGROUND

We are here concerned with the transmission of radio-frequency waves in the ground. As contrasted with transmission in air, the effects of the ground include: 1. A decrease in the velocity of propagation of the waves, as given by Harnwell,[2]

$$c' = c(\epsilon\mu)^{-1/2},$$

combined with a further dependence in a more complicated way on the conductivity, which decreases the velocity still further. In this relation c is the velocity of the waves in free space, μ is the permeability of the ground, and ϵ is the dielectric constant of the ground. 2. Reflection and refraction of the rays at the contacts between bodies of different dielectric constants or different conductivities as observed by Fritsch[3] and predicted by theory.[4] (Note: The magnetic permeability normally varies very little in the ground.) 3. Exponential attenuation of the amplitude, A, of the waves according to

$$A = A_0 e^{-2\pi f k z/c},$$

in which z is the distance in cms, f is the frequency in cycles per second, ρ is the resistivity of the ground in e. s. u., A_0 is the value of A where z is 0, and

$$k = \left[\frac{\mu}{2}\left(\left\{\epsilon^2 - \frac{4}{f^2\rho^2}\right\}^{1/2} - \epsilon\right)\right]^{1/2}.^{5}$$

[2] Harnwell, G. P. *Principles of electricity and electromagnetism.* McGraw-Hill, New York, p. 542.

[3] Fritsch, Volker. *Grundzüge der Funkgeologie.* Especially abb. 37, p. 40, and accompanying text. Friedr. Vieweg und Sohn, Braunschweig, 1939.

[4] Harnwell, *loc. cit.*, pp. 538–542.

[5] Joyce, J. W. *Electromagnetic absorption by rocks.* U. S. Bureau of Mines Technical Paper #497.

If we assume, for example, that: $\mu = 1$, $\epsilon = 10$, $f = 10^6$ cycles/sec, $\rho = 10^5$ ohm-cms $= 1.11 \times 10^{-7}$ e. s. u. (using Joyce's average value), a wave will be attenuated to 1/10 its amplitude in a distance of 50 meters; that is, nine-tenths of the amplitude will be absorbed in this distance under the assumed conditions. In a conductive earth this absorption is accomplished by the energy involved in producing earth currents. If a highly conductive body is present, it will contain a large current and will be surrounded by a secondary field, which may play an important part in producing weak areas.

The first direct test of the effects of faults and contacts was reported by Ernst Cloos.[6] He discovered weak spots over certain faults and contacts in the region just north of Baltimore, Maryland. He did not attempt to explain their cause. Cloos's findings have been corroborated in other regions by unpublished experiments.

Mr. W. M. Barrett has developed a method similar to that described below whereby he claims to be able to locate faults by their effect on the field produced by a portable broadcast station set up nearby.[7]

Since weak spots due to geologic influences are so poorly known, no complete, adequate picture of their cause can be given here. The incident radio field is elliptically polarized, being the sum of the primary field, any secondary fields present due to the induced ground currents, and any other fields reaching the point under consideration by other than the direct path from the sending station.[8] The latter include rays reflected and refracted at the surfaces between different rock bodies. The problem is simplified by the fact that when radio waves pass through the ground they are rapidly absorbed, so that the receiver is largely shielded from the complex reflections and refractions from geologic structures other than those quite near the receiving station.[9] However, surface features such as mountains may produce multiple incident rays; and gouge zones in faults, offset rock formations, sedimentary or igneous contacts, or differences in water table elevation across a fault may also be expected to have some effect of this sort.

[6] Cloos, *loc. cit.*

[7] Barrett, W. M. *Electrical apparatus and method for geological studies.* U. S. Patent #2,172,688.

[8] Heiland, C. A. *Geophysical Exploration.* Prentice-Hall, New York, 1940, pp. 815–818.

[9] Joyce, *loc. cit.*

According to Heiland weak spots probably are due to distortions of the equipotential lines near the contacts of good and poor conductors.[10] Heiland does not discuss the nature of this distortion. Barrett believes that the distortion of the radio-frequency field which he has observed over faults is the result of secondary fields.[11] Mingins, studying the effect of the ground on sky wave reception, has shown how the direction of the field would be affected by an underground conducting body.[12] The survey described in this paper, using the ground wave, found similar directional patterns poorly suggested over the San Jacinto fault. It is quite possible that fault planes have higher conductivities than the surrounding rocks because of the presence of certain minerals, or because they contain more water than the adjacent rocks. Currents in such conducting bodies are surrounded by secondary magnetic fields which at places may tend to balance out the primary field, and alter the direction of the resultant total field. This would explain why disturbed areas occur only at a few places along faults; only these places are sufficiently mineralized, or sufficiently saturated with water to cause a strong secondary field. Other parts of the fault are little or no more conductive than the adjacent rocks, and do not deform the electromagnetic field appreciably.

However, only conductors very near the surface will have appreciable effects at the surface. We have already shown that the amplitude of the waves is decreased to one-tenth of its initial value in approximately fifty meters under certain assumed conditions. Thus, if the conductor acted like a perfect reflector of energy at a depth of fifty meters, the return path of the secondary field would involve a further decrease of nine-tenths; or only one ten-thousandth of the energy starting from the surface would return for a vertically incident ray. This is an attenuation of about forty decibels. The situation, of course, is less simple than this; for the rays are not vertically incident, and in the case of the secondary field the induction component, which involves a decrease with the square of the distance, as well as the radiation component, is involved. Since it is doubtful if the conductor will redistribute more than a small fraction of the incident energy in a pattern giving weak spots, and as the absorption of the energy is so rapid, the expected secondary field is bound to be very small in com-

[10] Heiland, *loc. cit.*, pp. 651–656.

[11] Barrett, *loc. cit.*

[12] Mingins, C. R. *Electromagnetic wave fields near the earth's surface.* Proceedings of the Institute of Radio Engineers, Vol. 25, p. 1419, 1937.

parison with the primary field, and only a small anomaly can be expected except over extremely shallow conductors. The rapid absorption of energy with depth thus limits the depth of origin of any disturbance causing a weak area.

Both types of phenomena, interference by reflected and refracted rays, and secondary fields, are probably involved; and only further study will show the relative importance of each with respect to the cause of radio weak spots.

INSTRUMENTS AND FIELD PROCEDURE

Two sets of apparatus were used in the surveys to be described. The first was a portable directional range finder, consisting of a pair of loop antennae leading to a superheterodyne receiver mounted on a sturdy tripod. The antennae were rotatable about two perpendicular axes, and provided with an orienting compass, level bubbles, and scales for measuring the position of the loops. An auxiliary amplifier equipped with earphones and a milliammeter in the detector circuit to indicate signal strength could be hung on one leg of the tripod. The instrument could be used to indicate both signal strength and direction. However, as the meter sensitivity drifted badly, only directional data was considered dependable in interpreting the results.

The second set of apparatus was a portable field strength meter, consisting of a tuned radio-frequency receiver with two stages of radio-frequency amplification, and a detector-amplifier with milliammeter and phones in the plate circuit. This instrument was used in place of the other where only the field strength was to be measured. It was easier to handle, less dependent on direction, and readings could be taken much more rapidly than with the directional instrument.

As the anomalies expected from earlier surveys[13] were of the order of tens of decibels in intensity, no absolute calibrations of the meters were made, it being considered adequate to observe the relative variations in terms of meter reading where intensities were studied with the meter. It was realized that the meter scale was far from linear.

Both instruments were tuned to the standard broadcast range, and standard broadcast signals were studied in all cases.

The surveys consisted in taking readings of direction of the radio-frequency field, its intensity, or both, at regular intervals along series of parallel traverses across known faults; and plotting these readings

[13] Cloos, *loc. cit.*

against distance to determine if any regular variation of the field was associated with the faults. Traverses varied from a couple of hundred yards to over a mile in length. Because of the rapid attenuation of the waves in the ground already discussed, anomalies were expected only in the middle hundred yards of each traverse, greater length being run to provide some standard of normal terrain for comparison purposes, or to cover other geologic features than the main fault. Wherever possible the traverses were run in groups of parallel lines, the traverses being separated by ten to a hundred yards depending on their total length. This was to provide means of checking the regularity of occurrence of any anomalies found.

In some regions the field strength meter was carried in the baggage shelf behind the seat of a convertible coupe, and the audible output observed by listening with the earphones. The locations of sudden decreases in the field strength were recorded.

Care was taken to avoid, in so far as possible, areas where there was interference from nearby metallic conductors, and shadowing effects of hills, buildings or other causes. Normally, observations were taken between eight and four, sun time, since atmospheric conditions disturb radio reception most near sunrise and sunset.

LOCATION OF FIELD WORK

The first half of the survey to be described was run in southern California on several branches of the San Andreas fault. Here exposed rock was alluvium, with little or no surface expression of the fault where studied, and no difference between the rocks on either side of the fault near the surface except for an unmeasured difference in the height of the water table on either side. The main directional studies were made on the San Jacinto fault in the San Jacinto valley northwest of Hemet, Riverside County.

In New Jersey studies were limited to observation of intensity. Several branches of the Piedmont fault northeast of Somerville were examined. This fault, where studied, lies between pre-Cambrian schists on the northwest and Triassic sediments on the southeast. The land on the northwest is generally higher than the land on the southeast; therefore, the fault usually lies at the foot of a slope.

RESULTS

In making preliminary tests in the vicinity of Pasadena, California, it was soon clear that the complex network of pipes, wires and

other conductors in inhabited areas caused disturbances which made observations in such areas very difficult, if not impossible, to interpret. These tests showed that in densely inhabited regions and in regions of rugged topography, the radio-frequency fields are extremely irregular, and variations from other sources are sufficient to mask any patterns which might be expected to result from geologic structure.

In an examination of the San Bernardino region, California, conducted by listening to the field strength meter while driving along in a car, many weak areas were crossed, but only in a few cases were these inexplicable as resulting from overhead wires or other conductors. Since the geologic structure beneath this alluvium-covered area is not known, except that several branches of the San Andreas fault are present, relation of the few remaining weak areas to the geology was not determinable. There was no regular alignment of weak areas.

A similar survey in the Salton Basin, reputed to be an area of generally weak reception, indicated that although the surrounding mountains shielded it in large part from the ground waves of nearby stations, night reception of the sky waves from distant stations was excellent. Furthermore, a definite correlation was evidenced between relative elevation of the receiving station and the strength of reception, indicating that poor reception in the basin was largely the result of shadowing.

Similar surveys run in New Jersey over the Piedmont fault demonstrated a definite correlation between the weak spots and the fault, as Fig. 1 shows. The geology as shown here is taken from the U. S. G. S. Raritan Folio.[14] The first weak area northeast of Bissell diverges from the shown fault slightly, but as the fault cannot be located exactly at the surface, it is possible that the fault actually underlies the weak spot. In a like manner, west of Bissell three weak areas were noted, where only one fault is shown. At some places the Piedmont fault is known to have several closely spaced branches, and such may be the case here.

Several traverses were run in this vicinity taking absolute field strength readings, but the results were indefinite being complicated by the topography and scattered trees in the area. Curves I–III (Fig. 2) were obtained here. Distinct minima are shown by curves II and III at 80 and 70 paces respectively, and curve I may have a modified weakness at 70 paces. It is about here that the north branch of the

[14] Bayley, W. S., Salisbury, R. D., and Kummel, H. B *Geologic atlas of the United States, Raritan folio.* U. S. G. S., 1914.

fault might be expected from the qualitative examinations using the meter in the car. Less clear minima are shown on curves II and III where the fault is shown on the map. However, much of this variation doubtless resulted from changes in elevation of the ground. No evidence was found for a southern branch of the fault in traverses conducted over that part of the area.

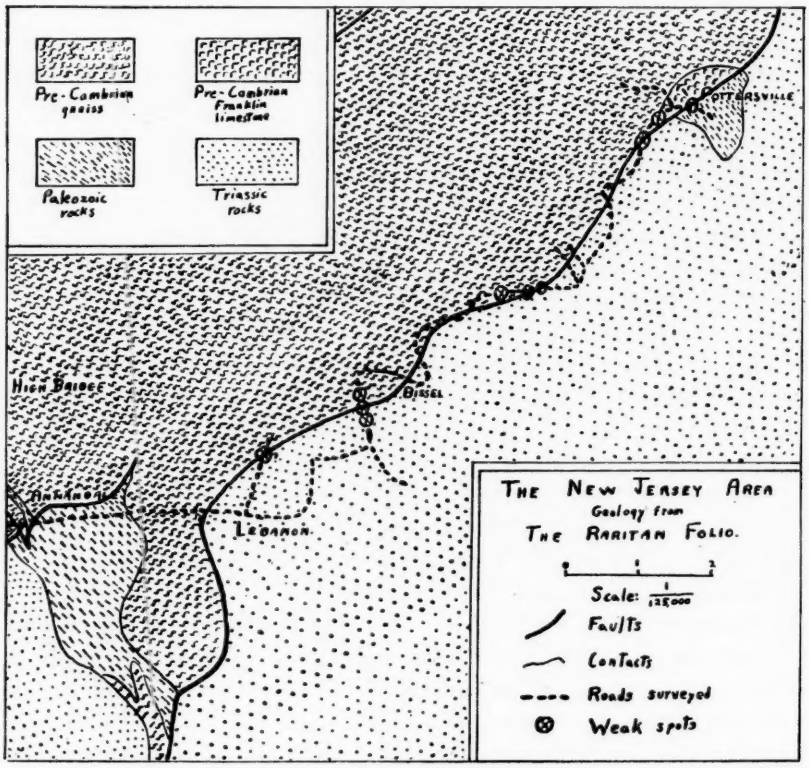


FIG. 1. Generalized geologic map of the New Jersey area, showing the Piedmont fault and the weak spots observed.

One major difficulty encountered in taking absolute field strength measurements of this sort is that where weak spots occur, only very weak fields, that is fields of low power, appear to be affected. This may have been an instrumental limitation, either in the electrical apparatus or in the ability of the ear to distinguish between varying intensities of sound. No appreciable change in the intensity of strong

fields is observed in driving across this area in the car listening to the field strength meter. Since, in taking absolute field strength readings, it was necessary to use strong fields in order to get appreciable meter deflection, this may explain why better results were not obtained.

The westernmost weak area north of Lebanon was not well located on the ground, and it is not certain that it lies directly over the fault; hence a question mark is drawn beside it. Many other weak areas were noted throughout the region examined, many of them on the fault, but as all of them could be attributed to other causes than the geology, they have not been shown here. It will be noted, also, that

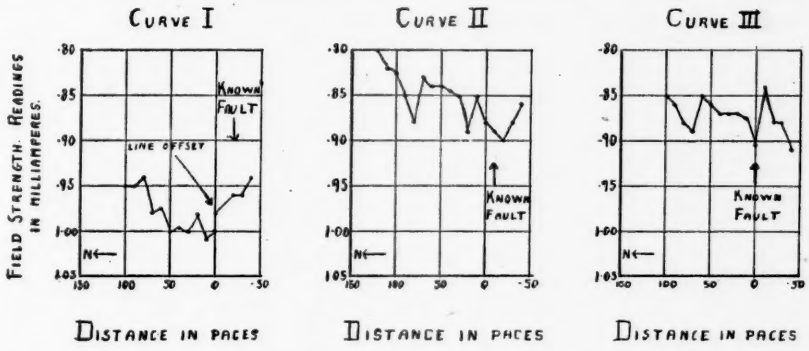


FIG. 2. Curves showing variations of field strength in the New Jersey area.

one weak spot lies on the contact of the Franklin limestone and the Losee gneiss west of Pottersville, a little distance from the fault. Each of the weak areas was visited at least three times on different days to be sure that each represented a persistent variation of the field.

Another interesting phenomenon is that in some cases a small maximum of field strength seemed to accompany the minimum, or weak spot, but this was never verified by quantitative readings.

Quantitative readings were taken on several series of traverses on the San Andreas fault east of Palm Springs, California, between Garnet Station and Desert Hot Springs. Here no effect of the fault on the radio field was noted. However, the effect of the overhead wires of the transcontinental telephone on the radio field was very clear (Fig. 3). The slight drift of the readings along this traverse probably is the result of shadowing by the San Jacinto mountains, as the drift was duplicated at different times of day on different days and running

the lines in opposite directions. The minor irregularities are the result of local topography and vegetation and constitute a "background level" of disturbance which precludes recognition of small variations in field strength due to geologic structure.

The main directional survey was conducted on the San Jacinto fault in several places in the San Jacinto valley. The results here are complicated by what is probably a standing wave pattern of some sort, not fully understood, perhaps due to reflection of the radio signals

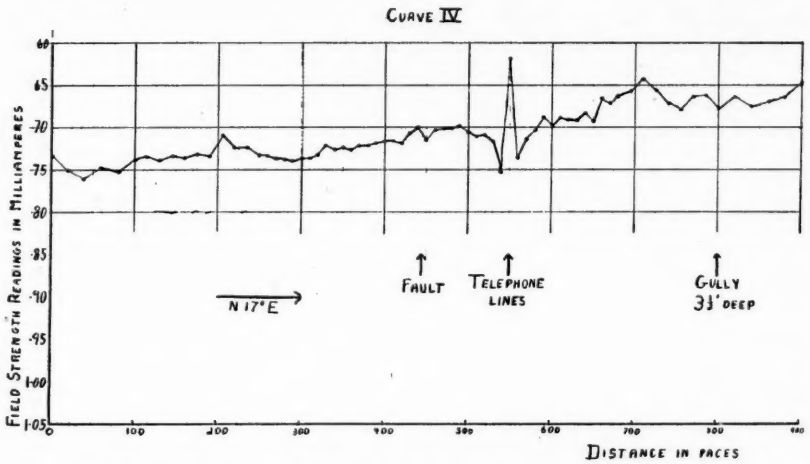


FIG. 3. Curve showing variations of field intensity in the Indio-Garnet area.

from the northeast side of the valley, or refraction around the hills to the southwest. One complication is that the separations of the maxima of the standing wave pattern are not always less than one-half of the wave length of the received signals. This may be the result of the lower velocity of the waves in the ground from which the interfering radiation may come. Superimposed on this are minor variations such as are shown at 80 paces on curves V and VI (Fig. 4). These occur very frequently over the places where the faults are believed to occur (their locations are not exactly known), and some similar variations occur elsewhere as at 160 paces on curve VI. Since each depends on the deviation from the normal of just one observation, and since they occur both over the faults and occasionally elsewhere, they are inconclusive, being only a second order variation in the curves. However, they do suggest that with more sensitive apparatus and more detailed study, more definite results might be obtained.

The results of these surveys may, therefore, be summarized:

1. In rugged and densely inhabited areas the variations in the fields due to non-geologic causes are so great that variations due to geologic causes are completely hidden.

2. A small variation in the radio-frequency field over faults such as the San Jacinto fault is suggested but not proven. Field strength

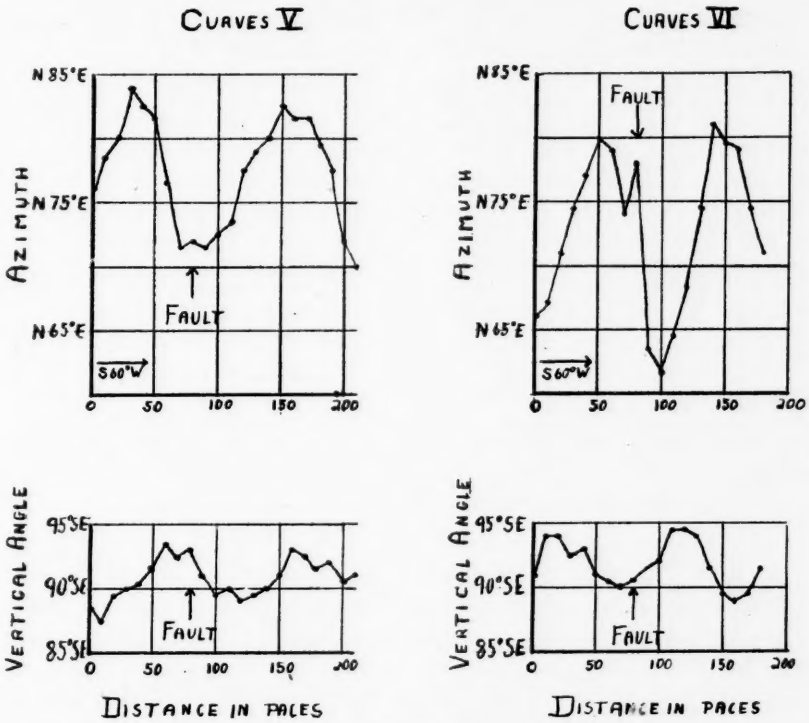


FIG. 4. Curves showing variations in dip and strike of the plane of polarization of the waves in the San Jacinto valley.

variations here are small, perhaps inappreciable. It is possible that the direction of the field varies over other types of faults; it is certain that the intensity sometimes does.

3. Faults and contacts coming to or nearly to the surface sometimes have areas of noticeably weak reception over their surface traces. Weak fields seem to be more strongly affected than strong ones. Why these anomalies occur at some places and not at others has not been shown, although theory suggests that a secondary field

resulting from conducting material in the fault plane is a factor. Faults between rocks of different composition such as the Piedmont fault in New Jersey appear to be more often associated with such phenomena than do faults whose surface traces are in alluvium.

The greatest need today is for the accumulation of more data on weak spots which are apparently due to geologic structure. When such places are found, they should be studied with respect to the frequencies which are affected, whether the angle between the fault and contact trace and the direction to the transmitter is involved, what range of field intensities are affected, and what variations there are in the direction of the field near the weak area. Also, whenever a clear-cut weak area is found, it should be carefully mapped to determine its size; and quantitative figures of the field strength should be recorded. It is especially important to determine what characteristics of the fault are present when weak spots occur. Further work of the type described would be facilitated by the use of apparatus of higher sensitivity. Standard broadcast signals are not as satisfactory for this purpose as a controlled local transmitter would be.

The study of directional effects is at least as promising as that of intensity variations.

More detailed work is needed on the theory of the reflection and refraction of radio waves at surfaces in or on the ground, including the calculation of expectable anomalies.

The author wishes to thank the many persons, especially Dr. G. W. Potapenko, who have aided him in this investigation. Special appreciation is due to the Division of Geological Sciences of the California Institute of Technology who provided the equipment used in this survey.

REVIEWS

Geophysical Investigations in the Tri-State Zinc and Lead Mining District. J. J. Jakosky, R. M. Dreyer, and Clyde H. Wilson. Engineering Experiment Station, University of Kansas, Lawrence, Kansas.

Early in 1941 the University of Kansas Engineering Experiment Station and the State Geological Survey of Kansas were invited, by several governmental agencies, to investigate the feasibility of using geophysical methods as a guide to ore prospecting in the Tri-State zinc and lead mining district of Kansas, Oklahoma, and Missouri. The increased demand for zinc and lead in the production of war materials made it appear desirable to attempt to develop some geophysical method or combination of methods which would be more rapid and less expensive than the present method of exploration by churn drilling now commonly employed in the Tri-State district.

A cooperative agreement was made between the Engineering Experiment Station, the State Geological Survey and the Tri-State Zinc and Lead Ore Producers' Association whereby the project was financed by the three organizations.

In order to simplify the initial experimental work all the geophysical investigations were made over areas where, as the result of intensive drilling, the geologic conditions and mode of ore occurrence were already known. In each area there was an attempt made to correlate the various geophysical anomalies with known geologic conditions. No attempt was made to prospect areas which had not been explored by drilling. This work will constitute the second period of investigation and will be undertaken shortly.

During the course of the investigation, the following types of geophysical surveys were conducted: electrical resistivity, geothermal, geochemical, gravity, natural earth potential, and magnetic. Results obtained in this investigation indicate that the geochemical, geothermal, and natural potential methods are negative as regards their diagnostic value in the delineation or location of ore bodies in that area.

The magnetic work gave results that are regional in character, and which are indicated as being useful as a guide in the interpretation of regional gravity anomalies.

The indications given by the regional gravity survey that regional gravity maxima are present and are deep-seated (as indicated by coincidence with regional magnetic maxima) make it appear advisable to recommend further regional gravity investigations. It appears possible, in the Mississippi Valley area, to separate potential zinc-lead producing areas from potentially non-productive areas, by the presence or absence of deep-seated gravity maxima.

Resistivity and gravity measurements can be used successfully to map structures reflected by variations in the elevation of the limestone surface. It is not possible geophysically to map structures within the limestone.

It has not been found possible, directly, to determine the presence of lead and zinc sulphides. It is possible, however, to use resistivity measurements in mapping certain structural and lithologic features associated at many places with ore mineralization, especially increased porosity of the limestone resulting from fracturing and brecciation. Such measurements, therefore, permit the selection of ground which might have productive possibilities, although an area could not definitely be classified as non-productive because of the absence of resistivity minima, or as necessarily productive because of the presence of resistivity minima. The judicious use of resistivity methods, however, should serve greatly to minimize the amount of exploratory drilling required, by directing drilling to the most favorable prospecting areas. On the average, a saving of

but one drill hole would pay for the cost of conducting detailed resistivity work over an area of 10 to 20 acres. The present normal prospecting procedure using drills, would require many hundreds of drill holes over such an area. Moreover, additional resistivity investigations have revealed methods of determining ore mineralization, which are described in more detail in the bulletin now in press.

Copies of the final bulletin may be obtained by directing a request to the Director, Engineering Experiment Station, University of Kansas, Lawrence, Kansas.

(Summary submitted by J. J. JAKOSKY)

PATENTS*

ELECTRICAL PROSPECTING

U.S. No. 2,300,709. G. A. Smith. Iss. 11/3/42. App. 1/10/41. Assign. Sperry-Sun Well Surveying Co.

Electrical Prospecting Method. An electrical porosity logging method using one electrode in the well and one on the surface; the circuit containing an applied potential of the same order as the electrofiltration potentials encountered and a high external resistance to minimize the effect of electrode resistance.

U.S. No. 2,304,739. J. P. Minton. Iss. 12/8/42. App. 2/5/41. Assign. Socony-Vacuum Oil Co.

Electrical Prospecting. A four-electrode method of electrical prospecting using a square wave and varying the fundamental frequency to control the penetration.

GEOCHEMICAL PROSPECTING

U.S. No. 2,305,082. C. R. Hocott. Iss. 12/15/42. App. 6/28/40. Assign. Standard Oil Development Co.

Geochemical Prospecting. A method of soil wax prospecting in which soil samples are extracted with a non-fluorescent solvent and the ultra-violet fluorescence of the extract measured by a photometric method.

U.S. No. 2,305,384. H. Hoover, Jr. Iss. 12/15/42. App. 5/27/40. Assign. Consolidated Engineering Corp.

Geophysical Prospecting Method. A method of soil analysis prospecting in which soil samples are taken from depths below the weathered layer as determined by a seismic or other geophysical method.

GRAVIMETRIC PROSPECTING

U.S. No. 2,301,396. A. Graf. Iss. 11/10/42. App. 4/6/38 and 3/17/37. Vested in Alien Property Custodian.

Gravity Meter. A spring type gravity meter whose mass carries a shutter which controls the light falling on a series of photocells.

U.S. No. 2,303,845. S. Krasnow. Iss. 12/1/42. App. 11/15/37.

Apparatus for the Measurement of Gravity. An inverted pendulum gravimeter made

* Abstracts by O. F. Ritzmann, Gulf Research & Development Co.

entirely of quartz sputtered for surface conductivity, control being obtained by tilting the system about a horizontal axis perpendicular to the suspension fiber and also by electrostatic attraction of a plate charged to several known potentials.

U.S. No. 2,304,191. L. M. Mott-Smith. Iss. 12/8/42. App. 5/19/39. Assign. Vincent J. Meyer.

Gravity Meter. A photoelectric indicating system for a gravity meter in which variations of intensity of the light source are eliminated by the use of a comparison light beam.

U.S. No. 2,304,324. P. S. Williams. Iss. 12/8/42. App. 7/27/39. Assign. Standard Oil Development Co.

Gravity Meter. A beam type gravity meter having a flat current carrying coil at the end of the beam so that electromagnetic forces can be set up to restore the beam to its null position.

U.S. No. 2,304,737. H. A. Maeder. Iss. 12/8/42. App. 3/6/40. Assign. Socony-Vacuum Oil Co.

Mass Clamp for Gravity Meters. A hydraulic clamping device for a gravimeter so arranged that a stop on one side of the clamp insures holding the mass in the same position each time it is clamped.

U.S. No. 2,304,748. D. H. Clewell. Iss. 12/8/42. App. 3/8/40. Assign. Socony-Vacuum Oil Co.

Gravity Meter. A gravity meter having a bar pivoted at one end and making a slight upward angle to the horizontal, the free end of the bar also having a torsion filament extending to a point some distance above the pivot.

SEISMOGRAPH PROSPECTING

U.S. No. 2,301,739. J. P. Minton and E. M. Shook. Iss. 11/10/42. App. 10/27/39. Assign. Socony-Vacuum Oil Co.

Gain Control for Seismograph Amplifiers. A method of controlling amplifier gain according to a preset time schedule so that the gain is high for first arrivals, decreases rapidly to permit recording shallow reflections, and then builds up gradually to a high value for deep reflections, adjustments on these time periods being provided.

U.S. No. 2,302,219. G. W. Hostetler. Iss. 11/17/42. App. 9/15/41. Assign. Olive S. Petty.

Infinite Period Seismometer. A geophone in which a long period is attained by adding an electromagnetic restoring force controlled by the amplifier and whose force tends to neutralize the restoring force of the spring.

U.S. No. 2,303,413. H. W. Washburn. Iss. 12/1/42. App. 7/28/39. Assign. Consolidated Engineering Corp.

Seismometer. A reluctance type seismometer having a stationary coil and whose suspended armature experiences a negative restoring force due to variable area and a counter-balancing positive restoring force due to variable air gap.

U.S. No. 2,303,357. H. Hoover, Jr. Iss. 12/1/42. App. 7/26/39. Assign. Consolidated Engineering Corp.

Seismic Wave Amplifier. A seismograph amplifier having stable operation over a wide range of AVC, the controlling voltage being applied to two elements of an amplifying tube both of which reduce gain at high signals, but one element having a negative curvature characteristic and the other a positive curvature characteristic.

U.S. No. 2,303,358. H. Hoover, Jr. Iss. 12/1/42. App. 7/28/39. Assign. Consolidated Engineering Corp.

Stable Seismic Wave Amplifier with Automatic Volume Control. A seismograph amplifier with AVC which at high signals reduces the main amplifier gain but at the same time increases the auxiliary control amplifier gain.

U.S. No. 2,304,738. M. D. McCarty. Iss. 12/8/42. App. 6/29/39. Assign. Socony-Vacuum Oil Co.

Seismograph. A geophone consisting of two vertical reluctance type instruments placed one above the other and arranged so that one unit may be rotated about a vertical axis with respect to the other so as to balance out electrical interference.

U.S. No. 2,304,740. J. P. Minton. Iss. 12/8/42. App. 3/6/40. Assign. Socony-Vacuum Oil Co.

Method for Recording Seismic Waves. A method of seismograph recording in which the conventional amplifier output has added to it one or more higher derivatives of the wave in order to improve the onset of reflections.

U.S. No. 2,305,383. H. Hoover, C. G. Morgan, and N. J. Christie. Iss. 12/15/42. App. 9/30/38 and 3/19/40. Assign. Consolidated Engineering Corp.

Geophysical Exploration System A series of two dimensional patterns of seismograph shot points and detector locations giving continuous control, with close detector locations offset to avoid ground roll and with transverse lines to simultaneously give the cross-line dip component of the reflecting horizon.

U.S. No. 2,305,543. M. D. McCarty Iss. 12/15/42. App. 2/5/41. Assign. Socony-Vacuum Oil Co.

Expander for Electrical Seismographs. An inverse feedback filtering system for seismograph amplifiers in which the frequencies to be accentuated are diverted, rectified, and applied to the grid of a preceding tube so as to increase its amplification.

U.S. No. 2,306,456. W. H. Mayne. Iss. 12/29/42. App. 6/1/40. Assign. Olive S. Petty.

Measuring and Recording Apparatus. Method and apparatus for recording the product of the outputs of two seismometers by using tubes operated at the vertex of a parabolic plate current-grid voltage curve.

U.S. No. 2,306,457. W. H. Mayne. Iss. 12/29/42. App. 6/1/40. Assign. Olive S. Petty.

Measuring and Recording Apparatus. A vacuum tube circuit for seismograph recording with the tube operated so that its output is proportional to the square of the grid voltage so as to accentuate large impulses.

U.S. No. 2,306,458. W. H. Mayne. Iss. 12/29/42. App. 6/1/40 and 6/24/41. Assign. Olive S. Petty.

Measuring and Recording Apparatus. Apparatus for seismograph recording in which an electrodynamometer type of oscillograph is used so that the deflection is proportional to the square of the seismometer signal.

U.S. No. 2,306,991. G. M. Groenendyke. Iss. 12/29/42. App. 3/23/39. Assign. Socony-Vacuum Oil Co.

Automatic Volume Control. An AVC circuit for seismograph amplifiers in which energy is taken from the plate of the output tube, amplified, rectified and applied to the suppressor grid of one or more amplifying tubes through a delay circuit.

WELL LOGGING AND SURVEYING

U.S. No. 2,300,206. J. B. Clark. Iss. 10/27/42. App. 10/30/41. Assign. Stanolind Oil and Gas Co.

Testing Well. A method of determining where fluid enters a well by conditioning the well with an immiscible liquid heavier than the fluid and electrically determining the lowermost point of entry, conditioning with an immiscible liquid lighter than the fluid and electrically determining the uppermost point of entry.

U.S. No. 2,301,307. T. E. McMahan. Iss. 11/10/42. App. 1/14/42. Assign. Richfield Oil Corp.

Means for Orienting Tools in Bore Holes. A whipstock orienting device consisting of a ball running to the lowest point of an annular race and a soft impression block which may be dropped to record the position of the ball together with an index on the whipstock and then withdrawn for examination.

U.S. No. 2,301,326. C. E. Reistle, Jr. Iss. 11/10/42. App. 11/3/39. Assign. Standard Oil Development Co.

Process for Obtaining Temperature Gradients in Bore Holes. A method of obtaining temperature at various points in a producing well which consists of lowering a conduit having a plug at the lower end and then running a thermometer inside the conduit.

U.S. No. 2,301,458. H. Salvatori. Iss. 11/10,42. App. 10/31/40. Assign. Stanolind Oil and Gas Co.

Seismic Well Logging. A method and apparatus for differential velocity well logging in which the impulse from an intermittent source is picked up by geophones above and below the source and these fire gas discharge tubes connected to a differentially indicating galvanometer.

U.S. No. 2,301,757. G. A. Smith. Iss. 11/10/42. App. 3/27/41. Assign. Sperry-Sun Well Surveying Co.

Well Surveying Instrument. A single shot electrically recording inclinometer whose electric circuit contains a switch held shut by a soluble pin, so that after a predetermined time the switch opens to prevent subsequent recording.

U.S. No. 2,302,247. J. Neufeld. Iss. 11/17/42. App. 4/22/40. Assign. Well Surveys, Inc.

Well Surveying Method and Apparatus. A neutron logging apparatus in which the primary neutron source is a material which is bombarded by alpha radiation, the alpha particles being directed in an optimum direction and generating neutrons which travel in this same direction.

U.S. No. 2,303,360. E. M. Irwin, R. M. Chenoweth, and R. H. Duval. Iss. 12/1/42. App. 9/7/37. Assign. Cooperative Development Co.

Apparatus for Determining Inclination of Well Bores. An inclinometer having a series of ball type levels of different sensitivities, contact of a ball with the outside edge causing a change in code of a buzzer noise carried to the surface by the drill stem and detected at the surface acoustically.

U.S. No. 2,303,688. R. E. Fearon. Iss. 12/1/42. App. 5/14/40. Assign. Well Surveys Inc.

Well Surveying Method and Apparatus. A neutron method of logging a well for aluminum in the formations by exposing the formations to a neutron radiation and at a later instant observing secondary radiation due to the decay of excited aluminum.

U.S. No. 2,303,709. A. J. F. Siegert. Iss. 12/1/42. App. 6/18/40. Assign. Texaco Development Corp.

Subsurface Prospecting. A method of increasing the intensity of a neutron source used in neutron logging by interposing a material in which nuclear fission can be induced between the primary source and the formations.

U.S. No. 2,304,051. R. F. Beers. Iss. 12/1/42. App. 2/5/40.

Means for Analyzing and Determining the Characteristics of the Geological Strata. A method of simultaneously making a seismic log and an electric log of a well by using phantom circuits without employing additional cables or electrodes.

U.S. No. 2,305,944. R. E. Wiley. Iss. 12/22/42. App. 9/23/40. Assign. Eastman Oil Well Survey Co.

Inclination Indicating Device. A single shot inclinometer using a plumb bob with a marking device on its point and a timing device which moves a record disk up to the plumb bob at a preset time.

MISCELLANEOUS

U.S. No. 2,299,076. P. T. Bynum. Iss. 10/20/42. App. 1/30/41.

Side Wall Sampler. A spring operated side wall sampling device which is lowered into the well in a cocked condition and released by a trigger tripped off by a go-devil.

U.S. No. 2,299,081. C. S. Draper. Iss. 10/20/42. App. 5/18/37 and 4/1/41. Assign. Research Corporation.

Vibration Measuring Apparatus. An electromagnetic torsional vibration detector for use on rotating machinery in which a permanent magnet acts as the seismic mass and a wound armature generates an emf in response to the torsional speed variations,

the entire assembly rotating with the shaft and having leads brought out through slip rings.

U.S. No. 2,299,907. W. E. Lawson and C. A. Woodbury. Iss. 10/27/42. App. 8/18/39. Assign. E. I. duPont de Nemours & Co.

Explosive Charge for Oil Wells. A well shooting explosive consisting of liquid nitroglycerine containing suspended crystalline salts which are water soluble and capable of being turned into gas by the explosion.

U.S. No. 2,300,384. E. L. Johnston. Iss. 10/27/42. App. 1/29/40. Assign. one-half to Delta Drilling Co.

Method of Locating Stuck Pipe in Wells. A method of locating where pipe is stuck before it is broken off by running inside the pipe an indicator line with an anchor, anchoring at various points and observing if there is any slackening of the wire line when a pull is applied to the pipe by the elevator.

U.S. No. 2,300,497. C. J. Glasser. Iss. 11/3/42. App. 11/26/38.

Galvanometer. A string galvanometer using a permanent magnet field.

U.S. No. 2,300,823. A. D. Whitman. Iss. 11/3/42. App. 12/18/39.

Indicating Device for Well Drills. A device operated through drill stem for drilling a small pilot hole ahead of the drill, the pilot drill being arranged to signal through changing resistance to mud circulation whenever a high electrical resistance is encountered or a characteristic frequency of pilot drill chatter is obtained.

U.S. No. 2,301,826. E. Steudel and J. Kaspar. Iss. 11/10/42. App. 2/21/40. Assign. General Electric Co.

Oscillograph. A multi-trace cathode ray oscillograph in which separate tubes are used and traces are superimposed by the use of partial reflecting mirrors and stereoscopic lenses.

U.S. No. 2,302,670. J. A. Buchanan, U.S.N. Iss. 11/24/42. App. 10/14/41.

Accelerometer. An indicating accelerometer in which damping is produced by friction of finely divided loose material contained inside the accelerometer steady mass.

U.S. No. 2,303,727. L. A. Douglas. Iss. 12/1/42. App. 6/10/41.

Means for Testing Underground Strata for the Fluid Content Thereof. A device for removing fluid from the side wall of a well, consisting of a vacuum chamber into which the fluid flows when the formation is pierced by an explosion or toggle driven tool.

U.S. No. 2,304,256. L. W. Huebel. Iss. 12/8/42. App. 1/15/40. Assign. National Lead Co.

Treatment of Well Drilling Fluids. The addition of sodium bicarbonate to drilling fluid before starting to drill out cement so as to prevent cement contamination and deterioration of the mud.

U.S. No. 2,304,330. C. E. Bannister. Iss. 12/8/42. App. 1/17/40.

Apparatus for Operating upon Lateral Walls in Earth Borings. A hydraulically driven

oscillating motor which may be lowered into a well and equipped with devices for cutting or unscrewing pipe.

U.S. No. 2,304,408. A. J. Holifield. Iss. 12/8/42. App. 3/30/42. Assign. One-fourth to E. H. Planck and one-half to M. H. Dees.

Gun Perforator. A mechanically fired gun perforator in which hydraulic pressure operates a series of firing pins which set off the cartridges.

U.S. No. 2,304,901. J. D. Eisler. Iss. 12/15/42. App. 2/19/40. Assign. Stanolind Oil and Gas Co.

Timing Device. A timer for a photographic recorder which consists of two coupled vibrators whose modes of vibration are at right angles and are placed in the light path so as to mark hundredth seconds and tenth seconds.

U.S. No. 2,304,910. D. G. C. Hare. Iss. 12/15/42. App. 5/29/40. Assign. The Texas Company.

Determination of Specific Gravity of Fluids. A method of continuously measuring the density of fluid in a pipe by irradiating the pipe with penetrating radiation and measuring the scattered intensity.

U.S. No. 2,305,139. A. J. Collins. Iss. 12/15/42. App. 2/9/40.

Firing Means for Well Perforating Guns. A gun perforator fired mechanically by the proper rotation of pipe on which it is carried.

U.S. No. 2,305,150. R. E. Fearon. Iss. 12/15/42. App. 7/16/40. Assign. Well Surveys, Inc.

Electrical Terminal. A gas tight electrical lead-in made of an insulating material having low thermal expansion and with a conductor cast or molded through it, the conductor having a varying cross section and higher thermal expansion so that it will always be tight.

U.S. No. 2,305,229. R. D. Alexander. Iss. 12/15/42. App. 12/8/41.

Signal Apparatus. An insulated electrode projecting through the wall of a well tubing and connected to a central prong which may be contacted by an insulated sleeve lowered on a cable through the tubing.

U.S. No. 2,305,267. E. E. Minor and S. A. Kilpatrick. Iss. 12/15/43. App. 8/5/39. Assign. Glenn L. Martin Co.

Vibration Measuring Apparatus. A fluid damped magnetic bridge type accelerometer and auxiliary equipment for recording and determining the characteristics of vibrations by a carrier wave method.

U.S. No. 2,306,118. A. H. Graham. Iss. 12/22/42. App. 3/20/41. Assign. Socony-Vacuum Oil Co.

Earth Boring Device. A shallow earth auger for seismograph shot holes or soil or soil gas analysis holes in which the bottom cutter is followed by a casing and the cuttings are continuously removed.

PUBLICATIONS RECEIVED

(The publications listed below were received since inauguration of this department in the January issue of *Geophysics*, Vol. VIII, No. 1. Articles cited are those which the Editor considered of particular interest to Society members.)

American Journal of Science, Vol. 240, 1942; Vol. 241, No. 1 (January, 1943), (New Haven).

Bulletin of the American Association of Petroleum Geologists, Vol. 26, No. 12 (December 1942); Vol. 27, No. 1 (January, 1943), *Recent Experimental and Geophysical Evidence of Mechanics of Salt-Dome Formation*, by L. L. Nettleton, pp. 51–63; Nos. 2, 3 (February, March, 1943), (Tulsa).

Economic Geology, Vol. XXXVII, No. 1 (January-February, 1942); Nos. 7, 8 (November, December, 1942); Vol. XXXVIII, No. 1 (January, February, 1943), (Lancaster).

Independent Petroleum Association of America Monthly, The. Vol. XIII, Nos. 8–10 (December, 1942–February, 1943). (Tulsa).

Journal of Applied Physics, Vol. 13, Nos. 11, 12 (November, December, 1942); Vol. 14, No. 1 (January, 1943). (Lancaster).

Journal of the Institute of Petroleum, Vol. 28, Nos. 225–26 (September, October, 1942); Vol. 28, No. 227 (November, 1942), *Graphical and Mechanical Determination of the True Dip from Magnetically Orientable Cores taken in Crooked Holes*, by G. D. Hobson, pp. 274–80. (Bungay, Suffolk, England).

Petroleum, Vol. V, Nos. 10, 12 (October, December, 1942); Vol. VI, No. 1 (January, 1943). (London).

Publicaciones del Instituto de Fisiografia y Geologia. "Cronica Bibliografica Mineralogia y Mineria, Geologia-Petrografia, Geografia-Paleontologia," by Alfredo Castellanos and Pierina Pasotti. C-1941, pp. 1–75. (Rosario, Argentina, 1941). *"A Proposito de los Generos Plohophorus, Nopachthus y Panochthus"* (3a. Parte), by Alfredo Castellanos. XI, pp. 417–592. (Rosario, Argentina, 1941).

Review of Scientific Instruments, The (through error, listed as *The Journal of Scientific Instruments* in the January "Publications Received"), Vol. 13, Nos. 11, 12 (November, December, 1942); Vol. 14, No. 1 (January, 1943), pp. 1–28. (Lancaster).

Revista de Ciencias, Vol. XLIV, Nos. 440–441 (June, September, 1942). (Lima, Peru).

United States Department of the Interior, Bureau of Mines:

Damage from Air Blast, Progress Report 1, by S. L. Windes. R. I. 3622 (February, 1942), 18 pp.

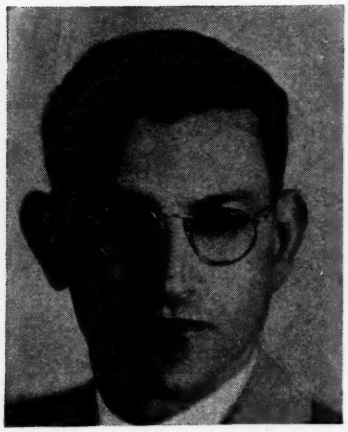
Design of Air-Blast Meter and Calibrating Equipment, by A. T. Ireland. Tech. Paper 635, 20 pp. (Washington, 1942).

Seismic Effects of Quarry Blasting, by J. R. Thoenen and S. L. Windes. Bul. 442, 83 pp. (Washington, 1942).

Tomorrow's Tools—Today! Vol. VIII, No. 3 (Third Quarter, 1942), 36 pp. *Correlation Between Electrical Logs and Radioactivity Logs*, by A. B. Winter, M. C. Bowsky, and J. C. Stick, Jr., pp. 4–7. "A Theory of the Distribution of Radioactivity in Marine Sedimentary Rocks," by Paul Weaver, pp. 30–32 (reprinted from *Geophysics*, Vol. VII, No. 2, April, 1942). (Los Angeles).

World Petroleum, Vol. 13, No. 13 (December, 1942); Vol. 14, Nos. 1, 2 (January, February, 1943). (New York).

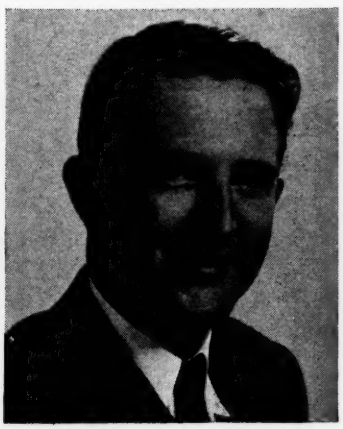
CONTRIBUTORS



M. B. WIDESS

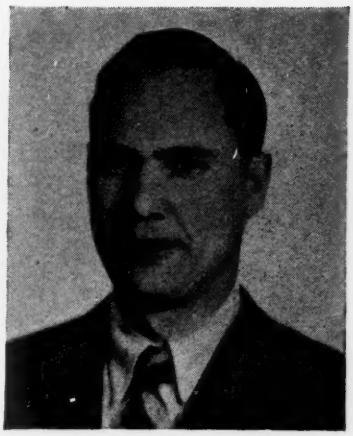
M. B. WIDESS received his B.S. degree in 1933 and Ph.D. degree in 1936 from the California Institute of Technology with major in electrical engineering. Since then he has been associated with Western Geophysical Company and Stanolind Oil and Gas Company. Dr. Widess' principal pursuit has been concerned with development of seismic interpretation. He is a member of the Seismological Society of America, the Tulsa Geological Society, and the Society of Exploration Geophysicists.

REED C. LAWLOR received the A.B. degree from the University of California at Los Angeles in 1932, with honors in Physics. He did graduate work in Physics at U.C.L.A. until March, 1934. At that time he was employed by Technicolor Motion Pictures, Inc., as an optical technician, and subsequently as an electrical inspector by the Los Angeles Department of Water and Power. He was employed as a physicist by the Rieber Laboratory from March, 1937, to July, 1938, at which time he entered the employ of Consolidated Engineering Corporation as a physicist and patent engineer. He is a member of Sigma Xi and Pi Mu Epsilon and is registered to practice before the Patent Office.

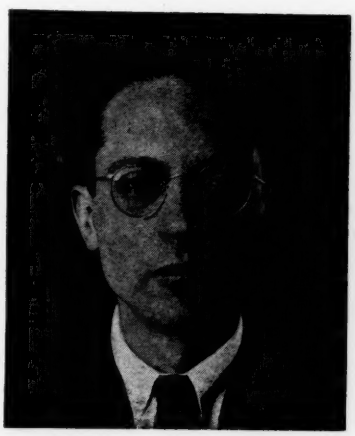


REED C. LAWLOR

HAAKON M. EVJEN received the degree of E.E. at Cornell in 1926, and the Ph.D. degree in 1929 from the California Institute of Technology. He was a National Research Fellow during 1931–33. Dr. Evjen was employed by the Gulf Oil Corporation during 1929–30, and the Shell Oil Company from 1934 to 1941. Since 1941 he has been associated with The Elflex Company of Houston. Dr. Evjen is a member of the American Physical Society, the American Association for the Advancement of Science, and the Society of Exploration Geophysicists.

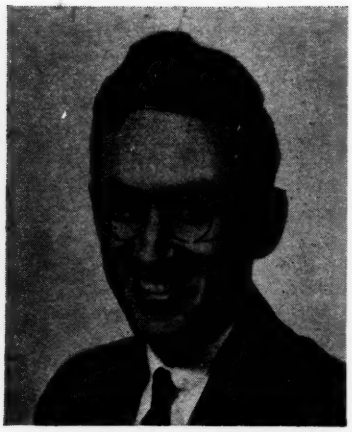


HAAKON M. EVJEN



S. S. WEST

S. S. WEST received his B.S. degree in 1930 and his Ph.D. degree in 1934 from the California Institute of Technology. He was employed by the U. S. Bureau of Standards from 1930 to 1931 as Junior Physicist in the Aerodynamics Section. From 1934 to 1936, he was research assistant in the Physics Department of Washington University in St. Louis, where he carried on research on electron scattering. From 1936 to 1938, he was Chief Physicist for Subterrex, engaged in the development of apparatus for electrical prospecting. Since January, 1939, he has been employed as research physicist in the laboratory of the Stanolind Oil and Gas Company in Tulsa. Dr. West is a member of the American Physical Society, the American Association for the Advancement of Science, the Society of Exploration Geophysicists, and the Federation of Architects, Engineers, Chemists, and Technicians.



B. F. HOWELL, JR., received his A.B. degree from Princeton University in 1939, and his M.Sc. degree in 1942 from the California Institute of Technology, where he was a graduate assistant and teaching fellow in the Balch Graduate School of the Geologic Sciences. He is now with the University of California War Research Laboratories at San Diego. Mr. Howell is a member of the American Geophysical Union, the American Institute of Mining and Metallurgical Engineers, Sigma Xi, and is a student member of the Society of Exploration Geophysicists.

B. F. HOWELL, JR.

Photographs and biographies of contributors to this issue not appearing above have appeared previously, as follows:

C. HEWITT DIX. Vol. VI, No. 4, p. 460 (October 1941).
C. A. HEILAND. Vol. VIII, No. 1, p. 76 (January 1943).
THOMAS A. ELKINS. Vol. VII, No. 1, p. 101 (January 1942).

THE SOCIETY ROUND TABLE

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The Executive Committee has approved for publication the names of the following candidates for membership in the Society. This publication does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it to the Secretary within thirty days. (Names of sponsors are placed beneath the name of each nominee.)

ACTIVE

Thomas William Buell
Roland F. Beers, W. W. Newton, Thos. R. Shugart

Roe William Carson
Bird G. Swan, L. F. Athy, H. R. Prescott

Claude Elmore Colvin
Roland F. Beers, W. W. Newton, Thos R. Shugart

Robert Benjamin Galeski
Norman J. Christie, Lawrence K. Morris, C. Hewitt Dix

Allen James Garber, Jr.
Robert H. Mansfield, Barthold W. Sorge, John J. Rupnik

Neal Harris Hardin, Jr.
Roland F. Beers, W. W. Newton, Thos. R. Shugart

Charles Leslie Heald
Barthold W. Sorge, Lawrence K. Morris, Robert H. Mansfield

Edward Pearsall Kennedy
Roland F. Beers, W. W. Newton, Thos. R. Shugart

Tom D. Mayes
Paul E. Nash, Jack C. Pollard, Henry C. Cortes

Walter R. Mitchell
John A. Gillin, C. G. McBurney, Charles C. Williams

Don Clifton Short
Barthold W. Sorge, C. Hewitt Dix, Cecil E. Reel

John Campbell Sproule
Malcolm Riess, J. D. Berwick, Clare N. Hurry

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William Wise Hollingsworth
R. S. Jackson, T. I. Harkins, A. L. Smith

Peter Jacobsen, Jr.
Leo W. Konz, Beno Gutenberg, S. Zimerman

Charles Edwards Myers
J. C. Pollard, Robert H. Ray, A. B. Hamil

John Thomas Randell, Jr.
Hans T. Lundberg, Mark C. Malamphy

James Kyle Riley, Jr.
R. S. Jackson, T. I. Harkins, D. B. Campbell
George Edward Schultis
R. W. Gemmer, A. B. Bryan, Francis A. Roberts
Mark Thomas Whelan
W. B. Kendall, L. H. Wise, H. Klaus
Floyd Eugene Wiancko
Norman J. Christie, Lawrence K. Morris, C. Hewitt Dix

PERSONAL ITEMS

CLAUDE WENDELL HORTON has left the Shell Oil Co., Inc., to accept a position as an Instructor in the Naval Radio Training School at the University of Houston. His residence address is 2616 Pemberton.

V. G. GABRIEL announces his removal from Los Angeles to 320 N. Maple Drive, Beverly Hills, California.

J. A. LEGGE, JR., formerly with the Standard Oil Co. of California, is now serving as Manager of the Computing Department of the United Geophysical Company.

The Houston Offices of Geophysical Service, Inc., have been moved from 821 to 1417 Esperson Building. H. B. PEACOCK, J. W. THOMAS, and VIRTIL TEUFEL may be reached at this new address.

Captain LEONARD F. UHRIG has been transferred to Maintenance Bn., A.P.O. 255, Camp Forrest, Tennessee.

PAUL C. REED, of the Gulf Res. and Dev. Co., has moved from Laurel to P. O. Box 562, Natchez, Mississippi.

FRANK SIEGEL, formerly with the Independent Exploration Co., has accepted employment as a computer with the Texas Co. He may be addressed at 569 Upper Mountain Ave., Montclair, N. J.

Major JOHN M. NASH is located in the Air Support Dept., Army Air Forces School of Applied Tactics, Orlando, Fla.

J. BYRON JONES is serving as an Engineer in the Mine Research Unit of the Naval Ordnance Laboratory. His residence address in Washington, D. C., is 117 Joliet Ave., S.W., Bellevue Gardens, Apt. 2A.

T. P. ELLSWORTH, Party Chief with the Western Geophysical Co., should be addressed at 560 Haberfelde Bldg., Bakersfield, California.

GEORGE M. BEVIER, Independent Geologist, has moved from San Antonio, Texas, to the Security Bldg., Pasadena, California.

Captain LYNN D. ERVIN, U. S. Marine Corps, gives his address as Battery G, Special Weapons Group, 9th Defense Bn., FMF, c/o Fleet Post Office, San Francisco, California.

ALBERT P. CRARY, formerly in foreign service with the Independent Exploration Co. in Colombia, and more recently Research Physicist at the Woods Hole Oceanographic Institution, has been released from that organization to accept an assignment as Party Chief for the Anglo-Iranian Oil Co. of England. He is now established with an American crew at Burgage Manor, Southwell, Notts, England.

A/C CHARLES BATES has moved from Los Angeles, Calif., to Route 2, Rockton, Ill.

CLINTON O. HURD is serving as Assistant Observer on a seismograph crew of the Cities Service Oil Co., and may be addressed at 309 S. Maple St., McPherson, Kansas.

C. L. PEKERIS, Columbia Univ. Div. of War Research, is located on the 11th Floor, 172 Fulton St., New York, N. Y.

ROBERT D. MILLER, formerly with the Shell Oil Co., Inc., is serving as Physicist with the Carnegie Inst. of Washington, Dept. of Terrestrial Magnetism, 5241 Broad Branch Rd., N.W., Washington, D. C.

T. J. O'DONNELL has advised the Society of his change of address from P. O. Box 733, Laurel, Miss., to 218 N. Craig St., Pittsburgh, Pennsylvania.

DAVID M. WEBER is in foreign service with the Mene Grande Oil Co., Aptdo. 45, Barcelona, Venezuela, as Seismograph Interpreter.

JAMES L. LAKE, JR., who served overseas as an officer with the Free French Forces in Great Britain and the Middle East, has returned to the United States and is serving as a Major, C. E., in the United States Army, Tank Destroyer Center, Camp Hood, Texas.

CHESLEY B. PICKLE, on leave of absence from the Standard Oil Co. of New Jersey, is serving as Physicist in the Naval Ordnance Laboratory, U. S. Navy Yard, Washington, D. C.

C. MAYNARD BOOS, 6917 Carleton Terrace, College Park, Md., is serving as Industrial Analyst with the War Production Board, Washington, D. C.

Lt. M. C. BOWSKY should be addressed at the Central Sig. C Unit Tng. Center, Camp Crowder, Missouri.

SAM E. SIMS, formerly with the American Republics Corp., is attending O. C. S. at Ft. Belvoir, Va. He may be addressed c/o O. R. Weyrich, 1819 Bolsover Rd., Houston, Texas.

HOWARD L. COBB has left the Mott-Smith Corp. to accept a position as Gravity Interpreter with the Atlantic Refining Co. in Dallas, Texas, where he may be addressed at 1404 Stirling Ave.

Cpl. A. A. HOTARD, who has been serving in the U. S. Army Air Corps since last July, is now based with the 12th Ferrying Squadron at the New Castle Army Air Base, Wilmington, Delaware.

Exploration Geophysics, written by J. J. JAKOSKY and printed by the Times-Mirror Press of Los Angeles, is now in its third printing, the Society has been advised.

ODELL C. OLSON has been commissioned 1st Lt. in the U. S. Marine Corps Reserves, and may be addressed at P. O. Box 349, Brady, Texas.

KENNEDY R. MARBLE, of the Carter Oil Co., should be addressed at Box 73, Holdrege, Nebraska.

M. S. MORRISON, of the Gulf Res. and Dev. Co., should be addressed at P. O. Drawer 2038, Pittsburgh, Pennsylvania.

BART W. SORGE, Supervisor with the United Geophysical Co., has moved to 2307 Arlington St., Bakersfield, Calif.

Former Ens. NAT H. PRADE has been advanced to the rank of Lt. (jg) in the U.S.N.R., and is serving as an Instructor at the Naval Mine Warfare School at Yorktown, Va. He left the Naval Ordnance Laboratory upon being commissioned in the U.S.N.R.

J. EUGENE STONES, of the Superior Oil Co., has been transferred from Fresno to P. O. Box 96, Bakersfield, California.

JAMES B. BATSON has been advanced to the rank of Captain in the Signal Corps, 53rd Signal Bn., Camp Bowie, Texas.

JAMES J. ROARK has left the employ of the Carter Oil Co. to accept a post as Instructor of Electrical Engineering at the Univ. of Arkansas. His address is 502 N. College St., Fayetteville, Arkansas.

L. J. PADDISON is on leave of absence from the Stanolind Oil and Gas Co. and is serving as Physicist in the Applied Physics Laboratory, The Johns Hopkins Univ., 8621 Georgia Ave., Silver Spring, Maryland.

CUTH K. SHEPHERD, 1st Lt. in the U. S. Army Infantry, advises the Society that his permanent address is 4005 Hanover, Dallas, Texas.

MAURICE SKLAR, of the Shell Oil Co., Inc., has been promoted to Seismologist and transferred to Shell's Eastern Area, with the postal address Box 31, Vandalia, Illinois.

RAYMOND A. PETERSON, who served temporarily with the Columbia Univ. Div. of the N. D. R. C. as Group Supervisor, has returned to his position as Geophysicist with the United Geophysical Co., 1255 E. Green St., Pasadena, California.

J. D. EISLER, on leave of absence from the Stanolind Oil and Gas Co., is doing war research work under an N. D. R. C. contract at the Franklin Institute, Philadelphia, Pennsylvania.

G. E. SWEET has been commissioned a Lt. in the U.S.N.R., and when last heard from, was at U. S. N. T. S. (Indoctrination), Rm. 779, Hollywood Beach Hotel, Hollywood, Fla.

R. G. PIETY, formerly with the Phillips Pet. Co., has accepted employment with the Farrand Optical Co., 4401 Bronx Blvd., New York, N. Y.

J. M. KILBORN, of the Gulf Res. and Dev. Co., is located at P. O. Drawer 506, Crowley, Louisiana.

R. M. BRADLEY, of the Cities Service Oil Co., has been transferred from Houston, Texas, to Bartlesville, Oklahoma, where he may be addressed at 701 Masonic Bldg.

Capt. HARRY R. IMLE, C. E., has advised the Society of his change of address to APO 722, Group A, Seattle, Washington.

O. A. SEAGER, of the Carter Oil Co., should be addressed at P. O. Box 2104, Billings, Montana.

JOHN MARSTON and J. E. DORRIS, of the Seismograph Service Corp., have returned from foreign service in Venezuela, and should be addressed at 709 Kennedy Bldg., Tulsa, Oklahoma.

J. G. FERGUSON, formerly with the Mott-Smith Corp., is serving as a Contract Employee in the Naval Ordnance Laboratory, U. S. Navy Yard, Washington, D. C. His residence address is 126 Irvington, S.W.

Capt. G. W. HOSTETLER, S. C., is located at 4009 Berkshire Rd., Detroit, Mich.

Lt. JOHN H. CROWELL, stationed in Washington with the U. S. Navy Dept. Bureau of Ships, has his residence at 7415 Lynnhurst, Chevy Chase, Maryland.

DAVID S. MUZZY, JR., of the Naval Ordnance Laboratory in Washington, D. C., is located at 506 Kentucky Ave., Alexandria, Va.

CHARLES C. LASH, also with the Naval Ordnance Laboratory, may be addressed at 2104 Cromwell Rd., Norfolk, Virginia.

CHARLES B. AIKEN, formerly of 34 Rockview Avenue, North Plainfield, N. J., is now located in Houston, Texas, at the Plaza Hotel.

LOUIS C. PAKISER, JR., should be addressed at 480 S. Raleigh St., Denver, Colorado.

IR. J. J. H. JANSEN M., formerly with N. V. de Bat. Pet. Mij. in Batavia, D. E. I., is a Lt. in the Dutch Air Force Army Flying School, Greenville, Mississippi.

PAUL BROWNING, until recently with the Standard Oil Co. of Venezuela, is now serving in the Petroleum Engineering Dept., Lago Pet. Corp., Maracaibo, Venezuela, South America.

THE DIVISION OF CULTURAL RELATIONS of the Department of State is sending microfilm copies of GEOPHYSICS and other technical journals to China.

THE GULF OIL CORPORATION has established a research assistantship in petroleum physics at the Massachusetts Institute of Technology. The recipient must qualify for a tuition scholarship and be a candidate for an advanced degree in the Department of Physics. The stipend will be $1,100 per school year.

THE UNITED STATES CIVIL SERVICE COMMISSION through Form No. 297 issued February 23, 1943, announces its need for men or women to fill the positions of:

Chief Technical and Scientific Aid, $2,600 a year;
Principal Technical and Scientific Aid, $2,300 a year;
Senior Technical and Scientific Aid, $2,000 a year;
Technical and Scientific Aid, $1,800 a year;
Assistant Technical and Scientific Aid, $1,620 a year;

in the optional branches of chemistry, geology, geophysics, mathematics, metallurgy, meteorology, physics, radio.

The Civil Service Commission also announces in Form No. 294, issued February 15, 1943, its need for Trainees, Scientific and Technical Aides, at $1,440 a year.

The above stated salaries are for a work-week of 40 hours. The standard work-week is 48 hours, with the overtime being paid at the usual rate.

THE SOCIETY OF EXPLORATION GEOPHYSICISTS
CONSTITUTION AND BY-LAWS

(As amended to April, 1943)

I. Name

This Association shall be called the "Society of Exploration Geophysicists."

II. Object

The object of this Association is to promote the science of geophysics especially as it applies to exploration.

III. Membership

A—Members

1. Any geophysicist of recognized standing shall be eligible to membership, whether or not he is engaged in petroleum geophysics or in geophysical prospecting.
2. Any physicist, mathematician, geologist, or engineer of recognized standing who is investigating a geophysical problem or problems shall be eligible to membership.
3. Any geologist of recognized standing who is not a geophysicist of recognized standing, but who is acting as chief, or division chief in charge of geophysical surveying, shall be eligible to membership.

B—Associates

1. Any geophysicist, geologist, engineer, mathematician, or physicist who is a graduate of an institution of recognized scientific standing who is engaged in geophysics and who is not eligible to membership shall be eligible to associate membership.
2. Any person who is not a graduate of an institution of recognized scientific standing and who is not eligible to membership and who has shown ability in a routine phase of geophysical work and who is in a position of responsibility in geophysical surveying shall be eligible to associate membership.
3. Any representative or employee of a firm or corporation engaged in suppiying equipment or supplies to the geophysical prospecting industry, provided such individual is the graduate of an institution of recognized scientific standing, or provided otherwise that such individual is qualified by adequate technical experience, shall be eligible to associate membership.
4. Associate members shall be known as associates.
5. Associates shall enjoy all the privileges of membership in the Society, save that they shall not hold office, sign applications for membership, or vote; neither shall they have the privilege of advertising their affiliation with the Society in professional cards or professional reports or otherwise.
6. The Executive Committee may advance to active membership, without the formality of application for such change, those associates who have, subsequent to election, fulfilled the requirements for active membership.

C—Student Members

1. Any graduate or undergraduate student in residence at a recognized university or college shall be eligible for student membership.

2. Student membership shall terminate one year after a student member ceases to be enrolled at a recognized university or college.
3. The privileges of student members shall be the same as those of associate members.

D—Election to Membership

1. Every candidate for admission as a member or associate shall submit a formal application on an application form authorized by the Executive Committee, signed by him, and endorsed by not less than three members who are in good standing, stating his training and experience and such other facts as the Executive Committee shall from time to time prescribe. Provided the Executive Committee, after due consideration, shall judge that the applicant's qualifications meet the requirements of the Constitution, they shall cause to be published in an appropriate publication the applicant's name and the names of his sponsors. If, after at least thirty days have elapsed since such publication, no reason is presented why the applicant should not be admitted, he shall be deemed eligible to membership or to associate membership, as the case may be, and shall be notified of his election. Provided the Executive Committee may accept applicants for either class of membership, who, because of their geographical location or because of their lack of acquaintance with active members of this Society, are unable to secure qualified sponsors, but who otherwise are eligible for membership. Applicants for student membership may be accepted as student members upon recommendation of a faculty member of the school they are attending, and with the unanimous approval of the Executive Committee.
2. An applicant for membership, on being notified of his election in writing, shall pay full membership dues for the current year and on making such payment shall be entitled to receive the regular Society publications for that year. Unless payment of dues is made within thirty (30) days by those living within the continental United States and within ninety (90) days by those living elsewhere, after notice has been mailed of his election, the Executive Committee may rescind the election of the applicant. Upon payment of dues, each applicant for membership shall be furnished with a membership card for the current year and until such written notice and card are received, he shall in no way be considered a member of the Society.

E—Honorary Members

1. The Executive Committee may from time to time and by unanimous action elect as honorary members persons who have contributed distinguished service to the cause of geophysics. Honorary members shall not be required to pay dues.

F—Code of Ethics

1. Membership of any class shall be contingent upon conformance with the established principles of professional ethics.

IV

A—Resignation—Suspension—Expulsion

1. Any member or associate may resign from the Society at any time. Such resignation shall be in writing and shall be accepted by the Executive Committee,

subject to the payment of all outstanding dues and obligations of the resigning member or associate.

2. Any member or associate who is more than one year delinquent (in arrears) in payment of dues shall be suspended from the Society. Any delinquent or suspended member or associate, at his own option, may request in writing that he be dropped from the Society and such request shall be granted by the Executive Committee. Any member or associate more than two years in arrears shall be dropped from the Society. The time of payment of delinquent dues for either one year or two years may be extended by unanimous vote of the Executive Committee.
3. Any member or associate who resigns or who is dropped under the provisions of Sections 1 and 2 of this article ceases to have any rights in the Society and ceases to incur further indebtedness to the Society.
4. Any person who has ceased to be a member or associate under Section 1 or Section 2 of this article may be re-instated by unanimous vote of the Executive Committee subject to the payment of any outstanding dues and obligations which were incurred prior to the date when he ceased to be a member or associate of the Society.
5. Any member or associate who, after being granted a hearing by the Executive Committee, shall be found guilty of a violation of the code of ethics of this Society or shall be found guilty of a violation of the established principles of professional ethics or shall be found guilty of having made a false or misleading statement in his application for membership in the Society, shall be asked to resign from the Society by unanimous vote of the Executive Committee. The decision of the Executive Committee in all matters pertaining to the interpretation and execution of the provisions of this section shall be final.

V. Officers and Their Duties

A—Officers

1. The officers of the Society shall be a President, a Vice-President, a Secretary-Treasurer, and an Editor. These, together with the Past President, shall constitute the Executive Committee and managers of the Society. Officers shall be elected for a term of one year with the exception of the Editor, who shall be elected for a term of three years.
2. A ticket of nominations for officers and representatives shall be prepared by a Committee on Nominations which shall consist of the President and the two qualified Past Presidents in order of precedence. Favorable action of this Committee shall be two out of three votes. This Committee shall nominate two candidates for President, one of whom shall be the retiring Vice-President, and two candidates for each of the other offices to be filled.

   The ticket prepared by the Nominating Committee, as well as any other ticket presented in writing and signed by at least twenty members in good standing, shall be submitted to the President by November 30. The President shall secure written acceptance of nominations from each candidate. The names of nominees shall be placed on the official ballot which shall be mailed to each member not later than December 15. Names of candidates shall be listed alphabetically except that the name of the retiring Vice-President shall occupy

first place on the ticket. Blank spaces shall be provided on the ballot for writing in nominations for each office.

Each member shall cast one vote for each officer to be elected and shall return his ballot to the Secretary-Treasurer. Ballots to be valid must be enclosed in an envelope carrying on the outside the written signature of the member submitting the ballot, and must be received by the Secretary-Treasurer at his officially recognized address not later than ten days prior to the Annual Meeting. Only ballots received from members in good standing as of a date ten days prior to the Annual Meeting shall be valid. The Secretary-Treasurer shall indicate which ballots are valid by initialing the enclosing envelope and shall deliver the ballots unopened to the Nominating Committee for counting.

The Nominating Committee shall count the ballots immediately before the Annual Business Meeting. The candidate receiving the greatest number of valid votes cast for an office shall be declared elected to that office. In case of a tie, the Nominating Committee shall decide by a secret vote which of the candidates tied shall be elected.

The announcement of the election shall be made as the first of the new business considered at the Annual Meeting.

3. No one shall hold the office of President for two consecutive years and no one shall hold any other office for more than two consecutive years except that of Editor.

B—Duties of Officers

1. The President shall be the presiding officer at all the meetings of the Society, shall take cognizance of the acts of the Society and of its officers, shall appoint such committees as are required for the purposes of the Society, and shall delegate members to represent the Society. He may, at his option, serve on, and may be chairman of, any committee.
2. The Vice-President shall assume the office of President in case of a vacancy from any cause in that office and shall assume the duties of President in case of the absence or disability of the latter. He shall also act as Chairman of the Program and Arrangements Committee of the Society.
3. The Secretary-Treasurer shall assume the duties of the President in case of the absence of both the President and Vice-President. He shall have charge of the financial affairs of the Society and shall annually submit reports as Secretary-Treasurer covering the fiscal year, which he shall arrange to have published in the next regular issue of the recognized organ of the Society. He shall receive all funds of the Society and, under the direction of the Executive Committee, shall disburse all funds of the Society. He shall cause an audit to be prepared annually by a public accountant at the expense of the Society. He shall give a bond, and shall cause to be bonded, all employees to whom authority may be delegated to handle Society funds. The amount of such bonds shall be set by the Executive Committee and the expense shall be borne by the Society. The funds of the Society shall be disbursed by check as authorized by the Executive Committee.
4. The Editor shall be in charge of the editorial business, shall submit an annual report of such business, shall have authority to solicit papers and material for the regular Society publication and for special publications, and may accept

or reject material offered for publication. He may appoint associate, regional, and special editors.

5. In the event of absence, disability or resignation of any member of the Executive Committee, the vacant place in the Committee shall be automatically filled by the next preceding qualified Past President who shall be known as Prior Past President.
6. The officers shall assume the duties of their respective offices immediately after the Annual Meeting following their election.

VI. Executive Committee—Meetings and Duties

A—Executive Committee

1. The Executive Committee shall consist of the President, Past President, Vice-President, Secretary-Treasurer, and Editor.

B—Meetings and Duties

1. The Executive Committee shall meet preceding the annual meeting and at the call of the President may hold meetings when and where thought advisable, to conduct the affairs of the Society. A joint meeting of the outgoing and incoming Executive Committees shall be held immediately after the close of the annual Society business meeting. Members of the Executive Committee may vote by proxy, mail or person on all matters which call for favorable or unanimous action.
2. The Executive Committee shall consider all nominations for membership and pass on the qualifications of the applicants, shall have control and management of the affairs and funds of the Society, shall determine the manner of publication, and shall designate the place of the annual meeting. They are empowered to establish a business headquarters for the Society, and to employ such persons as are needed to conduct the business of the Society. They are empowered to make investments of both general and special funds of the Society. Trust funds may be created giving to the trustees appointed for such purpose such discretion as to investments as seems desirable to the Executive Committee to accomplish any of its objects and purposes, but no such trust funds shall be created unless they are revocable upon ninety (90) days' notice. Favorable action shall consist of a favoring three out of five votes. Committee members may vote by person, proxy or in writing.

VII

A—Meetings

1. The Society shall hold at least one stated meeting each year, which shall be the annual meeting. This meeting shall be held at a time and place designated by the Executive Committee. At this meeting the proceedings of the preceding meeting shall be read, Society business shall be transacted, scientific papers shall be read and discussed, and results announced of the mail ballot for officers for the ensuing year.

VIII

A—Amendments

1. Amendments to this Constitution may be proposed by a resolution of the Executive Committee, by a Constitutional Committee appointed by the President,

or in writing by any ten members of the Society. All such resolutions or proposals must be submitted at the annual meeting of the Business Committee of the Society as provided in the By-Laws, and only the Business Committee shall make recommendations concerning proposed constitutional changes at the annual Society business meeting. If such recommendations by the Business Committee shall be favorably acted on at the annual Society business meeting, the Secretary-Treasurer shall arrange for a ballot of the membership by mail within thirty (30) days after said annual Society business meeting, and a majority vote of the ballots received within ninety (90) days of their mailing shall be sufficient to amend. The legality of all amendments must be determined by the Executive Committee prior to balloting.

B—Parliamentary Regulations

1. The rules contained in "Robert's Rules of Order, Revised" shall govern the Society in all cases to which they are applicable, and in which they are not inconsistent with the By-Laws or the special rules of order of this Society.

BY-LAWS

I

A—Dues

1. The fiscal year of the Society shall correspond with the calendar year.
2. The annual dues of members of the Society shall be five dollars ($5.00). The annual dues of associates for not to exceed six years after election shall be four dollars ($4.00); thereafter, the annual dues of such associates shall be five dollars ($5.00). The annual dues of student members shall be three dollars ($3.00). The annual dues are payable in advance on the first day of each calendar year. A bill shall be mailed to each member, associate, and student member before January first of each year, stating the amount of the annual dues and the penalty and conditions for default in payment. Members, associates, or student members who shall fail to pay their annual dues by March fifteenth shall not receive further copies of the regular Society publication, shall not be eligible to vote, nor shall they be privileged to buy Society special publications at prices made to the membership, until such arrears are met.

II

A—Publications

1. The proceedings of the annual meeting, the Constitution and By-Laws, and the papers presented at such meeting shall be published at the discretion of the Executive Committee in the regular publication or in such other form as the Executive Committee may decide best meets the needs of the membership of the Society.
2. The payment of annual dues for any fiscal year entitles the member or associate to receive without further charge the regular publication of the Society for that year. $3.00 ($3.50 foreign) of the annual dues is set aside for payment of the annual subscription to the Society Journal, GEOPHYSICS.
3. The Executive Committe may authorize the printing of special publications to be financed by the Society from its general, publication or special funds and

offered for sale to members and associates in good standing at not less than the cost of publication and distribution.

4. The Executive Committee may authorize the awarding of suitable prizes for the best papers submitted for publication in GEOPHYSICS under conditions designated by it.

III

A—Regional Sections, Technical Divisions, and Affiliated Societies

1. Regional sections of the Society may be established provided the members of such sections are members of the Society and shall perfect an organization and make application to the Executive Committee. The Executive Committee shall submit the application for action first by the Business Committee and second to the Society for a letter ballot as for a constitutional amendment, and provided that the Society may revoke the charter of any regional section by similar action.
2. The Executive Committee may arrange for the affiliation with the Society of duly organized groups or societies, which by object, aims, constitution, by-laws, or practice are developing the study of geophysics or petroleum technology. In like manner, the Executive Committee may arrange conditions for dissolution of such affiliations. Affiliation with the Society need not prevent affiliation with other scientific societies. Members of affiliated societies who are not members of the Society, shall not have the privilege of advertising their affiliation with the Society on professional cards or otherwise, but shall be entitled to receive the regular publication of the Society upon payment of a fee equivalent to that charged an associate member.

IV

A—District Representatives

1. The Executive Committee may cause to be elected district representatives from districts which it shall define by a local geographic grouping of the membership. Such districts shall be redesignated and redefined by the Executive Committee as often as seems advisable. Each district shall be entitled to one representative for each seventy-five members, but this shall not deprive any designated district of at least one representative. The representatives so apportioned shall be chosen from the membership of the district by a written ballot arranged by the Executive Committee. They shall hold office for two years, their term of office expiring at the close of the annual meeting. In so far as possible, these two-year terms shall be overlapping.

V

A—Business Committee

1. The Business Committee shall be a standing committee of the Society to act as a council and advisory board to the Executive Committee and the Society. This Committee shall consist of the Executive Committee, the Prior Past President, and the district representatives. Favorable action by the Business Committee shall consist of a favorable two-thirds vote. The Secretary-Treasurer shall act as Secretary of the business meeting. Members of this Committee may vote in person, by proxy, or in writing. The Business Committee shall meet the day before

the annual meeting at which time proposed changes in the Constitution or By-Laws may be considered, all old and new business shall be discussed, and recommendations may be voted for presentation at the annual meeting.

VI

A—Amendments

1. These By-Laws may be amended by favorable vote of the Business Committee, providing that such changes have been recommended and legality approved by the Executive Committee. Such amendments shall be published in the next regular number of the recognized organ of the Society.

SOCIETY OF EXPLORATION GEOPHYSICISTS
MEMBERSHIP LIST (MARCH, 1943)

*Acheson, C. H. (Gravity Meter and Magnetometer Party Chief), c/o Tropical Oil Co., Ltd., El Centro, Colombia, S. A.
Adams, Hal R. (Party Chief, Geotechnical Corp.), 1702 Tower Pet. Bldg., Dallas, Tex.
*Adams, Robert W. (Ensign, A-V(P), U.S.N.R.), P. O. Box 664, Reseda, Calif.
Adler, Joseph L. (Eastern and Foreign Mgr., Independent Exploration Co.), 901 Esperson Bldg., Houston, Tex.
Affleck, James (Geomagnetic Interpreter, Gulf Res. & Dev. Co.), P. O. Drawer 2038, Pittsburgh, Pa.
*Agee, F. H. (Seis. Party Chief, National Geophysical Co.), 123 S. Greenwood St., Lebanon, Tenn.
Agocs, William B. (Grad. Asst. in Physics, Lehigh Univ.), 940 Broadway, Bethlehem, Pa.
Aiken, Charles B. (Consulting Engineer), Plaza Hotel, Houston, Tex.
Alber, John L. (Operator), Geop. Dept., International Pet. Co., Negritos via Talara, Peru, S. A.
Albright, E. G. (St/Sgt/T, U. S. Army), c/o National Geophysical Co., Tower Pet. Bldg., Dallas, Tex.
Aldredge, R. F. (Geophysicist, Seismograph Service Corp.), 709 Kennedy Bldg., Tulsa, Okla.
*Alexander, Warren A. (U. S. Army), present address unknown.
Allen, Frank T. (Seismic Interpreter, Gulf Res. & Dev. Co.), Box 2038, Pittsburgh, Pa.
Allon, Michael (Geophysicist), c/o Gulf Res. & Dev. Co., Pauls Valley, Okla.
Alvarez, Manuel, Jr. (Geologist and Geophysicist, Petroleos Mexicanos), Ignacio Mariscal 12-A, Mexico City, D. F.
Anderson, O. W. (Chief of Party), c/o Stanolind Oil and Gas Co., Box 591, Tulsa, Okla.
Antes, Leland L. (Eng. Science and Management Defense Training, U. S. Office of Education, Univ. of Texas), 2405 Red River, Austin, Tex.
Arick, M. B. (Lt., U. S. Army Air Corps), 1010 W. Indiana St., Midland, Tex.
Arnett, R. D. (Supervisor, National Geophysical Co.), 3405 Colgate, Dallas, Tex.
Arthur, Marion A. (Engr., Office of Scientific Res. & Dev.), Dept. of Terrestrial Magnetism, Carnegie Inst. of Washington, Washington, D. C.
Athy, L. F. (Chief Geophysicist), Geophysical Dept., Continental Oil Co., Ponca City, Okla.
Augenthaler, R. L. (Geologist and Geophysicist), c/o Std. Oil Co. of British Columbia, 700 Lancaster Bldg., Calgary, Alberta, Canada.
Augustat, George (Seis. Party Chief, Geophysical Service, Inc.), 1311 Republic Bank Bldg., Dallas, Tex.
Aurand, Harry A. (Consulting Geologist and Geophysicist), 1350 Bellaire St., Denver, Colo.

*Backman, John E. (Party Mgr., Gulf Res. and Dev. Co.), P. O. Drawer 2038, Pittsburgh, Pa.
Bader, Glenn E. (Chief Seismic Computer), Humble Oil and Refg. Co., 802 Humble Bldg., Houston, Tex.
Bailey, Lothrop H. (Asst. Geophysicist, Gulf Res. and Dev. Co.), P. O. Drawer 2038, Pittsburgh, Pa.
Baird, John (Assoc. Engr., U. S. Navy Dept., Bureau of Ordnance), 402 Pine, Boulder, Colo.
Baird, Walter D. (Party Chief, Geophysical Service, Inc.), P. O. Box 1528, Stockton, Calif.
Baker, Malcolm C. (Computer, Humble Oil and Refg. Co.), 202 Humble Bldg., Houston, Tex.

* Associate Member. † Student Member. ‡ Honorary Member.

The occupations and addresses noted herein are based on the most recent information sent the Society. It will be appreciated if any incorrect listings are called to the attention of the Business Manager at P. O. Box 1925, Washington, D. C.

*Ballard, James A. (Sr. Seismic Computer, Seismograph Service Corp.), 221 Ratan Ave., Lajunta, Colo.
Banta, H. E. (Research Physicist, Independent Exploration Co.), 1922 W. Gray, Houston, Tex.
Barger, Thomas C. (Geophysicist), California-Arabian Std. Oil Co., Bahrein Island, Persian Gulf.
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Thompson, R. R.
Woods, J. P.

Everett
Haskell, Norman A.

Harvard
Leet, L. Don

Lincoln
Beers, Roland F.

Taunton
Church, Joseph H.

Weston
Linehan, Daniel, S. J.

Woods Hole
Ewing, Maurice

MICHIGAN

Detroit
Hostetler, G. W.

MINNESOTA

Minneapolis
Weisbrich, R. A.

MISSISSIPPI

Camp Shelby
Lynn, Ralph D.

Canton
Howard, G. C.

Greenville
Jansen M., Ir. J. J. H.

Hattiesburg
Dreyfus, Robert M.

Hazlehurst
Gallaway, Roy Lee
Zimerman, Sam

Laurel
Strange, Booth B.

Natchez
Reed, Paul C.

MISSOURI

Camp Crowder
Bowsky, Merle C.

Fort Leonard Wood
Lambrecht, Forrest F.

Joplin
Latimer, M. W.
Seyffert, Willis A.

Saint Louis
Macelwane, James B., S. J.
Stearn, Noel H.

MONTANA

Billings
Seager, O. A.

NEBRASKA

Holdrege
Marble, Kennedy R.

NEW JERSEY

Asbury Park
Loring, Ralph C.

Elizabeth
Jameson, M. H.

Gibbstown
Burrows, L. A.

Montclair
Siegel, Frank

Westfield
Flude, J. W.

NEW YORK

Amawalk
Kelly, Sherwin F.

Canton
Crary, Albert P.

Garden City
Doolittle, Russell C.
Peoples, J. A., Jr.

Hempstead
White, Gifford E.
Witt, M. K., Jr.

Mineola
Westrick, Edmond W.

New York
Gibbon, H. A.
Hardy, Willis W.
Hubbard, Bela
Lynch, J. Joseph, S. J.
Milstein, Mark N.
Olson, W. S.
Piety, R. G.
Pratt, W. E.
Skeels, D. C.
Weichert, R. F., Jr.
Whiton, Herman F.
Zavoico, Basil B.

Rochester
Tompkins, Frederick A.

Wellsville
Young, Wilber H., Jr.

West Point
Honnell, P. M.

NORTH CAROLINA

Davidson
Foster, Edward S., Jr.

OHIO

Dayton
Kearby, J. G.
Koenig, Palmer E.
Meador, Bernal M.
Nash, Cleve C.

Mount Healthy
Day, Charles E.

OKLAHOMA

Ardmore
Moose, Dale H.

Bartlesville
Beck, August F.
Bradley, R. M.
Courtier, William H.
Dietert, Arthur E.
Dissler, Ernest
Ericson, Harry B.
Haig, Ardris
Hintze, A. J.
Kidd, Robert L.
Miller, Vincent

Duncan
Elam, Daniel F.

Enid
Clifton, R. L.

Norman
Roberts, Francis A.
Schriever, William

Oklahoma City
McMullin, E. F.
Schaeffer, Hugh C.

Pauls Valley
Allon, Michael

Ponca City
Athy, L. F.
Beeth, Donald
Crawford, John M.
DeGood, R. G.
Erickson, Anton
Haber, A. F.
Handley, E. J.
Hughes, Roland F.
Jordan, C. K.
Leathers, C. H.
Mount, E. L.

Northcutt, W. C.
Prescott, H. R.
Richards, L. J.
Searcy, Frank
Swan, Bird G.
Vorheis, Byron
Warren, Paul R.
Whitehead, L. E.

Seminole
Mercier, Vincent J.

Shawnee
Bazhaw, W. O.
Lukens, John P.

Tulsa
Aldredge, R. F.
Anderson, O. W.
Barthelmes, Albert J.
Becker, H. C.
Bible, John L.
Bills, Robert N.
Bishop, F. L.
Blight, Richard E.
Borman, F. W.
Born, Milton C.
Born, W. T.
Boucher, F. G.
Brewer, Ralph R., Jr.
Bryan, A. B.
Buffum, C. E.
Bullock, Robert L.
Burg, Kenneth E.
Burton, R. H.
Cady, Francis H.
Clark, R. C.
Coffin, R. Clare
Cooper, Jack R.
Craig, Robert L.
Dahlberg, Robert S., Jr.
Davenport, Robert
Davis, D. R.
Dorris, James E.
Dyk, Karl
Emanuel, Vincent
Emrick, D. G.
Faust, L. Y.
Ferguson, John L.
Gemmer, R. W.
Gilliam, J. T.
Gilliland, J. R.
Gilmour, Andrew
Green, W. G.
Harlton, Bruce H.
Hawkins, J. E.
Hopkins, James S.
Hurry, Clare N.
Innes, Arland I.
Irby, W. L.
Itten, Howard
Jeffers, Paul H.
Kempsky, Phillip J.
Kendall, G. D.
Kendall, W. B.
Lawrence, K. M.
Leedy, F. B.
Lester, O. C., Jr.
Manhart, T. A.
Marsh, Samuel R.
Marston, John
Martin, Dick
McNatt, E. M.
Mehringer, A. P.
Moore, Homer C.
Neufeld, J.
Owen, J. E.
Perry, W. B.
Rankin, C. T.
Reid, A. C.
Rich, J. M.
Richardson, J. W.
Rickel, Wesley K.
Ricker, Norman
Riess, Malcolm
Romberg, Marvin
Ross, Charles M.
Rutledge, Richard B.
Seaman, L. O.
Sharpe, Joseph A.
Sibley, W. B.
Siegert, Arnold J. F.
Silverman, Daniel
Sparks, Neil R.
Stover, Edward B., Jr.
Strachan, Clyde G.
Swearingen, A. C.
Taylor, Albert
Taylor, Garvin L.
Teague, Norman P.
Thomsen, Erik
Thralls, H. M.
Van Croy, Stefan
Van Valkenburgh, J. C.
Vernon, Jess
Wagoner, George E.
Walton, George G.
Watson, Robert J.
Weatherby, B. B.
West, S. Stewart
Westby, G. H.
Wilcox, Stanley W.
Williams, P. S.
Winn, Clayton N.
Winnek, J. R.
Wise, L. H.

OREGON

Pendleton
Fleishman, Sam

Portland
Williston, Samuel H.

PENNSYLVANIA

Bethlehem
Agocs, William B.

Philadelphia
Bazzoni, Charles B.
Eisler, Joseph D.

Pittsburgh
Affleck, James
Allen, Frank T.
Backman, John E.
Bailey, Lothrop H.
Boots, Paul H.
Bradford, Donald C.
Butler, Mark D.
Butler, W. W.
Caldwell, C. L.
Cerveny, Philip F.
Cook, D. E.
Copeland, R. J.
DeWoody, D. A.
Diveley, Paul R.
Dombart, William F.
Eckhardt, E. A.
Elkins, Thomas A.
Gardner, Louis W.
Gealy, Wendell B.
Gemmell, Howard F.
Gunn, J. E.
Hammer, Sigmund I.
Hastings, W. K.
Herron, Robert C.
Hollobaugh, Robert C.
Hoylman, H. Wayne
Jones, Ralph E.
Jones, R. W.
Kerbow, R. B.
McCracken, Guy I.
McGee, John E.
Meszaros, W. A.
Meyer, Edgar J.
Morrison, M. S.
Mortlock, Frank O.
Muffly, Gary
Muskat, Morris
Nettleton, L. L.
O'Donnell, Thomas J.
Palmer, E. M.
Palmer, Loyal D.
Peters, Leo J.
Reiser, Robert G.
Ritzmann, O. F.
Robinson, John L., Jr.
Robinson, W. Bernard
Ross, R. B.
Scott, D. L.
Smith, Douglas H.
Staples, Guy W.
Swartz, Charles A.
Texter, John W.

Tomlinson, John B.
Unger, Earle E.
Waring, W. W.
Watson, George R.
Wert, Carl M.
Woodard, D. H.
Wyckoff, R. D.

State College
Pirson, Sylvain J.

TENNESSEE

Lebanon
Agee, F. H.

Nashville
Uhrig, Leonard F.

TEXAS

Abilene
Hale, C. Russell

Athens
Smitherman, Lynn A.

Austin
Antes, Leland L.
Konz, Leo W.
Romberg, Frederick E.

Beaumont
Ellis, L. G.
Hollingsworth, W. E.
Nahas, J. N.
Rose, H. W.
Smiley, W. G., Jr.

Bellaire
Wolf, Alexander

Brady
Olson, O. C.

Camp Bowie
Batson, James B.

Corpus Christi
Howerton, Bert P.

Dallas
Adams, Hal R.
Albright, E. G.
Arnett, R. D.
Augustat, George
Bevan, Thomas J.
Brown, H. Hallock
Browning, K. A.
Buckner, Guy L., Jr.
Chandler, Lyman, Jr.
Cobb, Howard L.
Coit, R. B.
Collingwood, Douglas M.
Cortes, Henry C.
Dahm, C. G.
De Golyer, E. L.
Dexter, Laurence N.
Dobyns, D. R.
Doering, John
Doss, C. L.
Douglas, Norvel
Elms, R. G.
Fain, Edgar A.
Farren, Paul
Fisher, Barney
Gaby, Phil P.
Gillin, John A.
Green, Cecil H.
Harkey, W. J.
Hieatt, Herbert F.
Hurt, Worth B.
Jackson, Robert W.
Jones, M. P.
Jonsson, J. E.
Karcher, J. C.
Kelsey, Martin C.
Kennedy, Frank H., Jr.
Lahee, Frederic H.
Lester, John A.
Lovinggood, Toby
MacNaughton, Lewis W.
Mann, Neil W.
McBurney, Charles G.
McDermott, Eugene
Meade, George N.
Menefee, James C.
Minton, J. P.
Moon, Jake
Moore, Charles M., Jr.
Nash, Paul E.
Newton, W. W.
Paslay, L. C.
Pernell, J. H.
Perryman, J. D.
Pittman, C. V. A.
Pollei, Donald W.
Pratt, R. B.
Ransone, W. R.
Reagor, Edward C.
Renner, Darwin S.
Rice, E. R., Jr.
Rollins, J. Frank
Sargent, R. L.
Schley, Woodruff H.
Seiffert, Wesley H.
Seiler, George E.
Shepherd, Cuth K.
Shugart, T. R.
Smith, C. B.
Stanton, Austin N.
Steel, D. M.
Storm, Alfred E.
Stulken, E. J.
Tabor, E. M.
Van Cleave, R. F.
Walczak, Michael J.
White, Rex H.
Williams, Charles C.
Williams, Floyd J.
Williams, Richard
Wilson, E. E.
Wooley, William C.

Danbury
Garrett, William M.

Denison
Wood, Arthur B.

Ellington Field
Shafer, Russell E.

Fort Ringgold
Schoellhorn, Henry, III

Fort Worth
Harris, Sidon
Ledyard, Paul H.
Lovejoy, J. B.
Morris, James L.
Sandidge, Irl, Jr.
Wilson, John H.

Goliad
Hargis, A. V.

Hallettsville
Manes, O. B.

Hamilton
Stiles, Elisabeth

Houston
Adler, Joseph L.
Aiken, Charles B.
Bader, Glenn E.
Baker, Malcolm C.
Banta, H. E.
Barnette, L. Atmar M.
Bennett, Roy F.
Berg, G. A.
Berndes, A. E., Jr.
Bertram, A. C.
Black, J. P.
Blau, L. W.
Blevins, David C., III
Bolinger, John W.
Brooks, O. D.
Broussard, C. H.
Broussard, D. F.
Brown, Hart
Bryan, Carl L.
Bugbee, J. M.
Burnett, Arthur C.
Busch, H. W.
Byers, J. W.
Campbell, D. B., Jr.
Campbell, F. F.
Carlton, Dave P.
Carr, G. W.
Child, V. E.
Conrad, P. P.

Cowles, Laurence G.
Cox, Harris
Crary, Donald
Culbertson, J. A.
Davis, Donald M.
Deacon, L. E.
Deussen, Alexander
Doll, H. G.
Donnally, Chester J.
Duty, Robert S., Jr.
Eby, A. N.
Eby, J. Brian
Epperson, R. S.
Evjen, H. M.
Falkenhagen, H. M.
Fecht, Arthur J.
Ferris, Craig
Fohs, F. Julius
Freel, J. F.
Frosch, Alex
Gardner, Derry H.
Garrett, L. P.
Gibson, M. O.
Giezendanner, S. S.
Gilmore, John A.
Goldstone, Frank
Gomez, J. S.
Goss, Henry V.
Griffin, I. M., Jr.
Hafner, W.
Hall, T. O.
Hamil, A. B.
Happel, Henry H.
Harkins, T. I.
Harrington, G. H.
Haynes, C. J.
Henderson, Homer I.
Herzenberg, A. J.
Hibbler, Alfred J.
Hibbler, M. E.
Hightower, C. H.
Hillyer, Ray H.
Hoard, J. O.
Holekamp, O. G.
Holmer, Ralph C.
Horton, C. W.
Horvitz, Leo
Houghton, H. M.
Houston, Charles E.
Hubby, L. M.
Hughes, Darrell S.
Hunzicker, A. A.
Ivy, John S.
Jackson, G. L.
Jackson, Ralph S.
Jerome, J. Glen
Jett, J. E.
Jones, Harold H.
Judson, Sidney A.
Kannenstine, Fabian M.
Ladner, Albert L.
Lamb, George B.
La Rue, James E.
La Rue, Wilton W.
Lawhorn, O. T.
Lay, Roy L.
Leonardon, E. G.
Lewis, Karl E.
Lewis, W. B.
Low, R. M.
Lowe, C. R.
MacAllister, C. T.
MacMahon, A. M.
Marr, John D.
Marti, J. E.
Martyn, Phil F.
McCollum, Burton
McCollum, Elton V.
McCullagh, John, Jr.
McDonnold, H. W.
McMurry, Howard
Merritt, H. W.
Millet, M. J.
Mitchell, George D., Jr.
Montgomery, George P., Jr.
Moore, Arthur A., Jr.
Morgan, Wesley H.
Mower, L. K.
Neff, W. D.
Neuman, L. J.
Nisle, Robert G.
Osterhoudt, W. J.
Palmer, John E.
Palmer, R. L.
Patrick, H. G.
Peacock, H. B.
Pollard, J. C.
Ray, Robert H.
Reed, Charles F.
Reynolds, F. F.
Rolshausen, F. W.
Rosaire, E. E.
Rulfs, G. W., Jr.
Rust, W. M., Jr.
Sanders, C. W.
Saville, W. G.
Schafer, Sidney
Scherb, Ivan V.
Schiflett, H. L.
Schmidt, Henry
Schmuck, R. H.
Schofield, G. A.
Scholl, Louis A., Jr.
Schumacher, J. P.
Schwennesen, A. T.
Selig, A. L.
Sherar, E. S.
Sherar, Stuart
Shore, H. F.
Sims, Sam E.
Sisson, H. H.
Smith, Aylwin L.
Stone, George B.
Sundt, O. F.
Taylor, Josiah
Taylor, W. H.
Teufel, Virgil W.
Theis, R. H.
Thomas, J. W.
Treybig, B. H., Jr.
Urbom, O. W.
Van Melle, F. A.
Van Weelden, A.
Walker, J. E.
Walker, R. Y., Jr.
Wallace, C. R.
Walsh, T. N.
Ware, J. H.
Watt, J. S.
Weatherby, S. Preston
Weaver, Paul
Wilber, Roscoe C., Jr.
Williams, E. D.
Wilson, H. A.
Winter, A. B.
Yeates, F. L.
Zazvorka, Jerry, Jr.
Zimmerman, C. C.
Zirbel, N. N.

Liberty
Lee, Walter B., Jr.

Lubbock
Klaus, H.
Penney, A. B.

Marshall
Lea, N. J.

Maypearl
Thomas, Earl

Midland
Arick, M. B.
McKinsey, M. H.
Winter, Niles B.

Navasota
Fetzer, E. L.

Odessa
Dana, R. H.
England, C. M.

Orange
Sessions, Sanson S.

Pearsall
Pranglin, John A.

Pecos
Ruhlen, W. W.

Riverside
Weinzierl, John F.

San Antonio
Benke, M. L.
Crawford, Paul D.
Dahlberg, Jack K.
De Loach, Edward L.
Imle, John F.
Kelley W. W.
Mayfield, W. I.
McAlister, C. H.
Moore, Marion J.
Moore, W. Lee
Narvarte, P. E.
Petty, Dabney E.
Petty, O. S.
Roberts, Homer E.
Souther, J. B.
Whitsitt, C. D.

Seagoville
Stubbe, G.

Terrell
Carter, Ray K.

Three Rivers
Head, E. I.
West, Thomas S.
Whitley, W. M.

Throckmorton
Geyer, Robert L.
Jackson, O. B.

Tulia
Graham, Burleson

Tyler
McCaleb, M. M.
Thomas, J. W., Jr.

Wichita Falls
Kunkel, T. L.

UTAH

Gold Hill
Wilson, Clyde H.

VIRGINIA

Alexandria
Lipson, Edward
Muzzey, David S., Jr.
Odenweller, Keith H.

Arlington
Cash, Harvey, Jr.
Morgan, Chas. Gill
Wenz, Gordon M.
Wetzel, W. W.

Charlottesville
Stoneham, S. C.

Fort Belvoir
Maxwell, Joseph M.

Norfolk
Lash, Charles C.

Yorktown
Prade, Nat H.

WASHINGTON

Seattle
Imle, Harry R.
Lambert, G. D.

WYOMING

Rawlins
Johnston, Frank M.

FOREIGN

AUSTRALIA

Sydney
Brown, Donald R.
Maliphant, H. C.

BRITISH WEST INDIES

Trinidad

Pointe-a-Pierre
Brotherhood, G. Roy
Higgins, G. E.

CANADA

Cadillac
Koulomzine, Th.

Calgary
Augenthaler, R. L.
Bickel, Harold C.
Chesher, C. E.
Sohlberg, R. G.

Moncton
Hole, H. W.

Toronto
Berwick, J. D.
Lundberg, Hans

Vancouver
Paterson, R. G.

CANAL ZONE

Cristobal
Lehman, Frank F.

Diablo Heights
Carson, J. P.

CENTRAL AMERICA

Costa Rica

San Jose
Wallis, W. E.

EGYPT

Cairo
Haight, H. W.

ENGLAND

Cheshire
Germain-Jones, D. T.

London
Johnson, G. R.
Richards, T. C.
Shaw, H.
Templeton, James C.

Notts
Davies, Richard

Surrey
Jones, John H.

FRANCE

Saint Gaudens
Schlumberger, Marcel

GERMANY

Breslau
Mintrop, L.

Hannover
Brinckmeier, Georg
Schleusener, A.

IRAQ

Basrah
Barnett, G. W. T.

MEXICO

Mexico City
Alvarez, Manuel, Jr.
Rojas, A. Garcia

Sonora
Brenner, Morris

PERSIAN GULF

Bahrein Island
Barger, Thomas C.

ROUMANIA

Ploesti
Small, Walter M.

SOUTH AMERICA

Argentina

Buenos Aires
Martin, Rodolfo
Ramaccioni, D.
Rey, Pedro
Rozlosnik, Andres

Brazil

Rio de Janeiro
Do Amaral, Irnack Carvalho
Oddone, D. S.

Colombia

Barranquilla
Martin, W. Obier
Reichert, H. C.
Silva, Will
Williams, C. E.

Bogota
Bonillas, Ygnacio
Del Rio M., Alejandro
Etherington, Thomas J.
Hazen, George H.
Itria, Oswald
Samuels, G. H., Jr.

El Centro
Acheson, C. H.

Ecuador

Guayaquil
Durham, Charles A.
Tallman, R. H.

Quito
Barksdale, G. L.

Peru

Negritos
Alber, John L.

Uruguay

Montevideo
Vercesi, D. R.

Venezuela

Barcelona
Weber, David M.

Caracas
Benton, Robert T.
Cody, C. C.
Cornett, J. R.
Franks, W. E.
Frost, Holloway
Gerdes, C. H.
Kaufmann G., F.
Kamen-Kaye, M.
Kimble, Henry R.
Lee, B. D.
Luchsinger C., F.
Merritt, W. C.
Mix, Adrian E.
Moorman, H. R.
Perkinson, Floyd
Speirs, George H.

Caripito
Burney, James H.
Swift, Edwin M.

Maracaibo
Browning, Paul
Howe, Ralph H.
Klein-Haneveld, A.

SWITZERLAND

Zurich
Fisch, W.

UNION OF SOUTH AFRICA

Johannesburg
Weiss, Oscar